The MEG II experiment and a new idea for the precision test on LUV with the LXe detector

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The University of Tokyo
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JSPS Core-to-Core Program

東京大学
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International Center for Elementary Particle Physics
The University of Tokyo

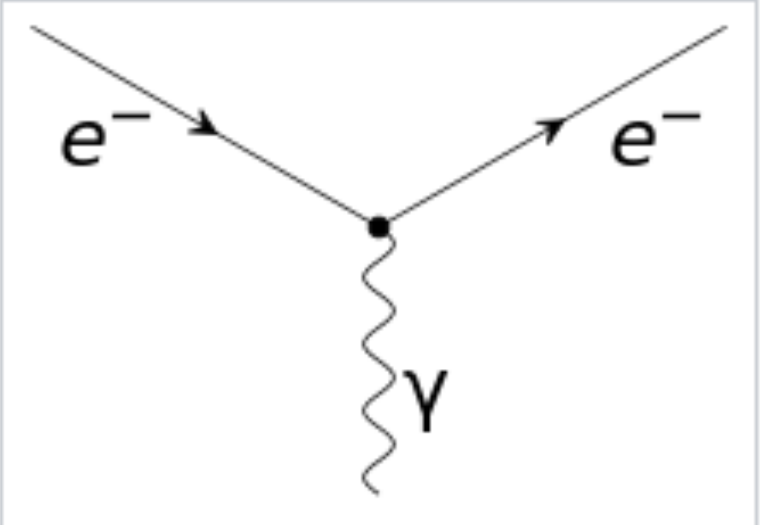
Topics

- Introduction
- The MEG II experiment
- The LXe detector
- New idea for the LFUV measurement

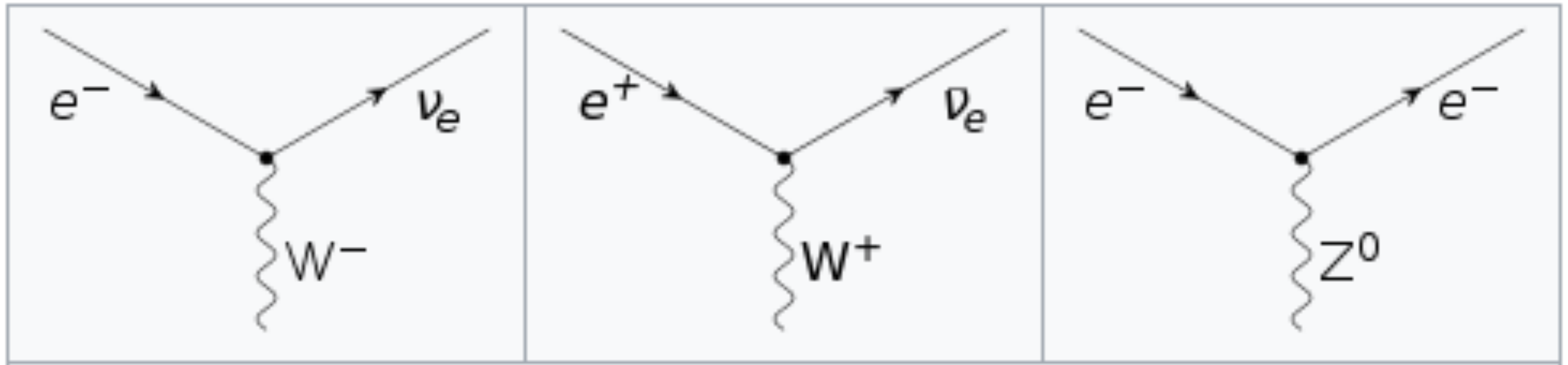
Martin, Vincenzo

Lepton Universality

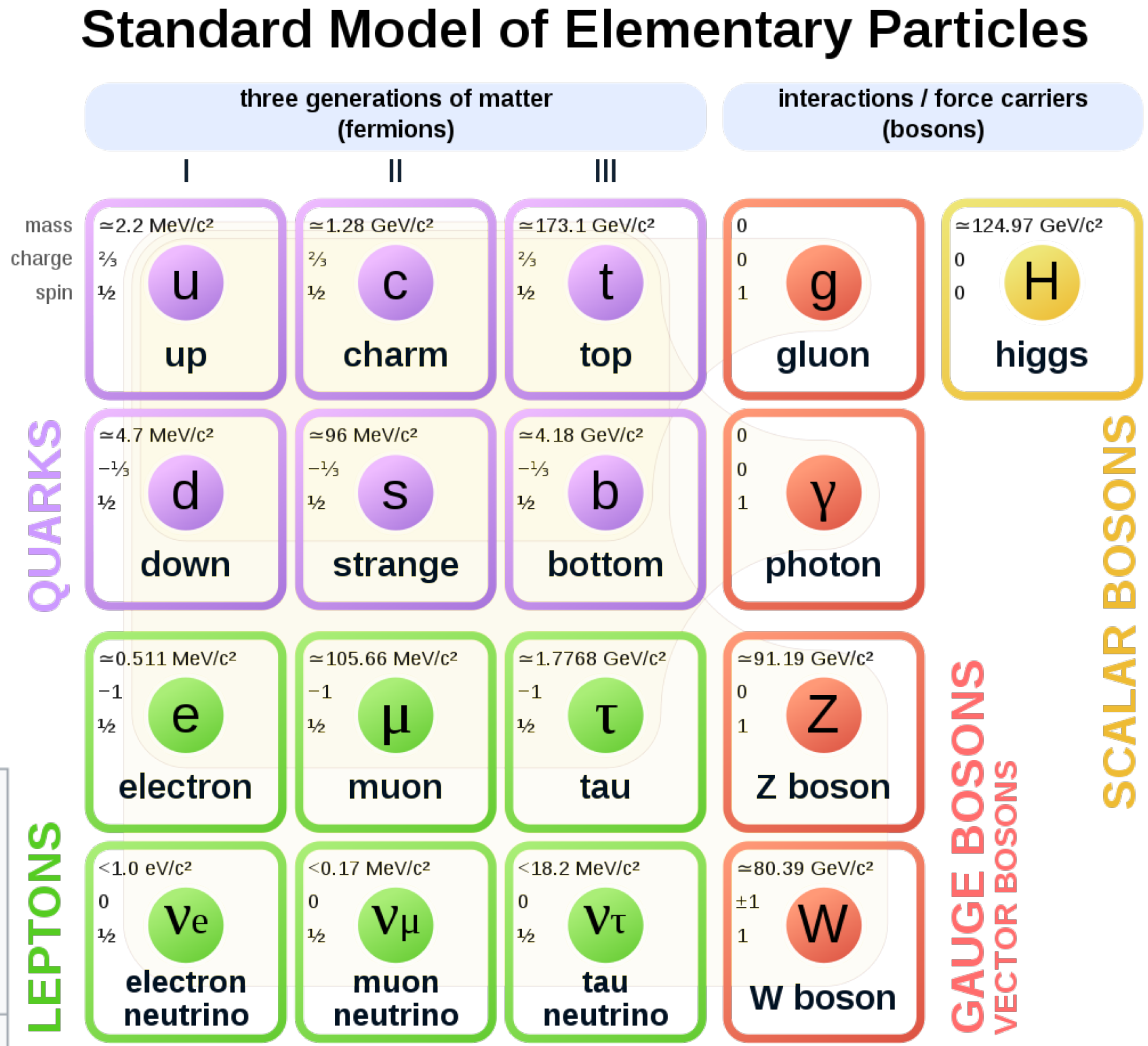
- The standard model assumes equal electroweak couplings of the three lepton generations
  - Q=1 : e, μ, τ
  - Q=0 : ν_e, ν_μ, ν_τ
  - $g_e = g_\mu = g_\tau$



Lepton–photon interaction



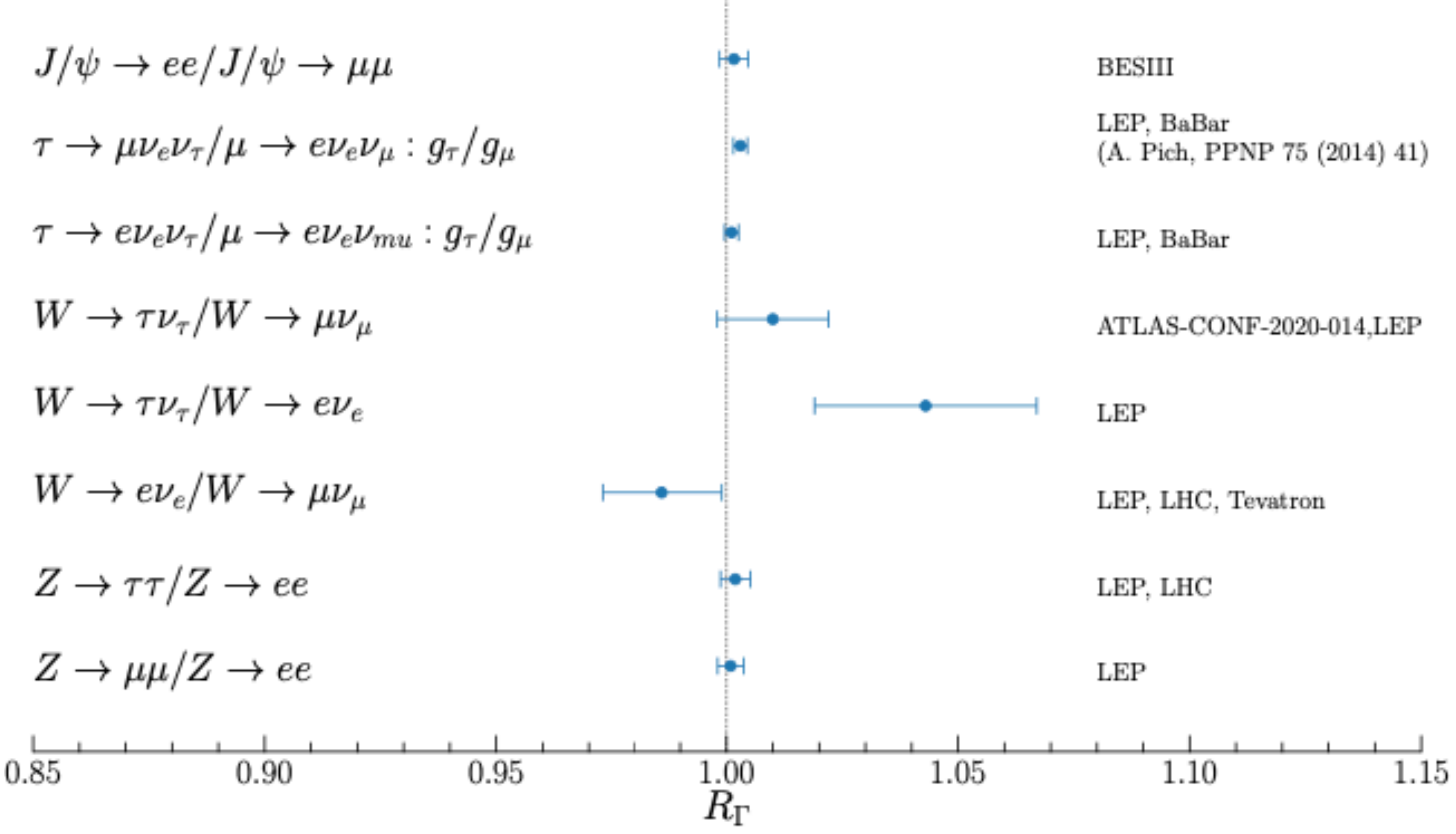
The weak interactions of the first generation leptons.



Lepton Flavor Universality

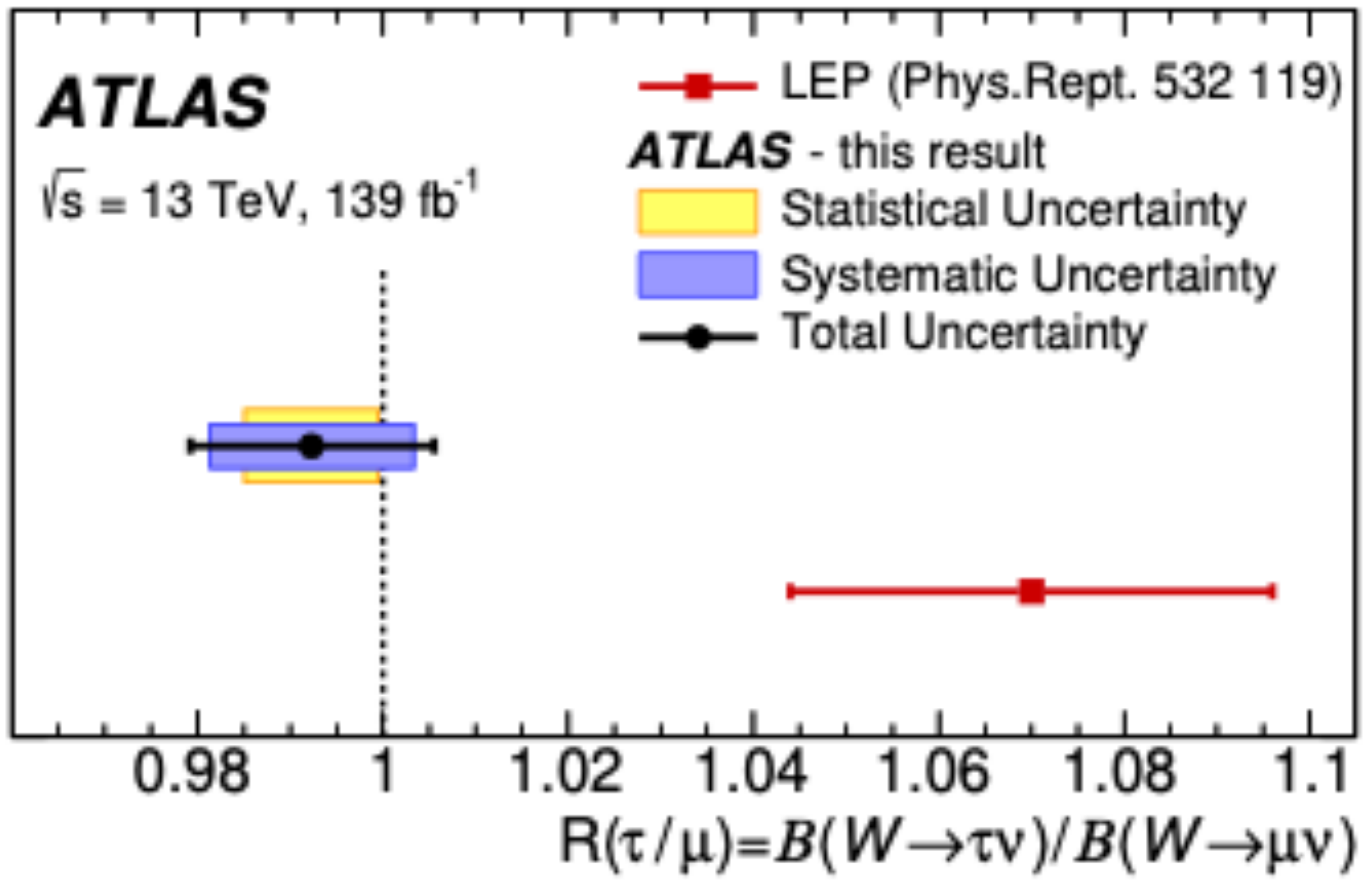
- Tested in many different decays
  - Studied in high-precision measurements of π, K, τ, B, and W decays
- Not generally true in SM extensions
  - Any significant observation of LFU violation is a sign of New Physics

[PDG2020, Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]



ICHEP2020

arXiv:2007.14040 (subm. Nature Phys.)

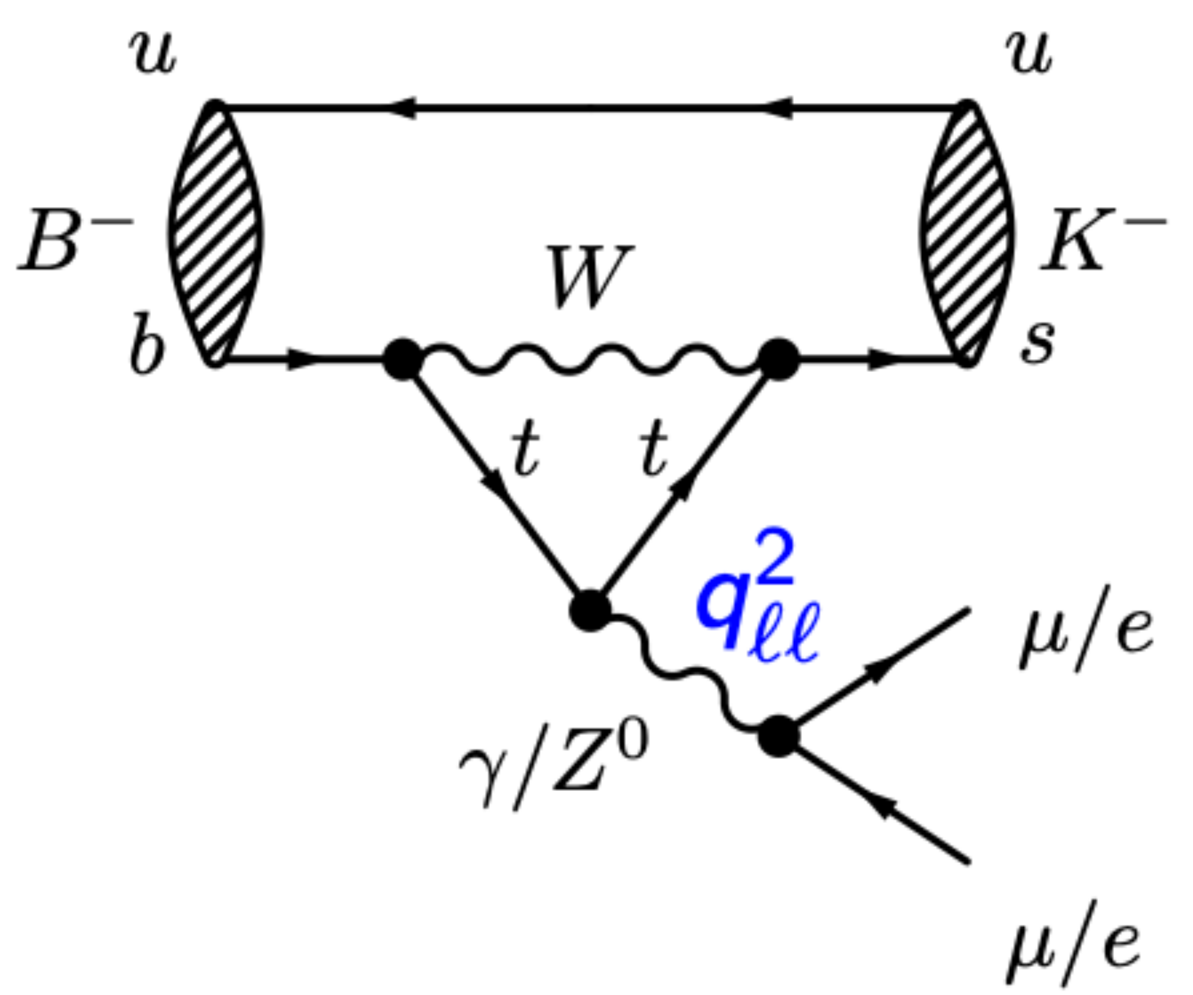


R = BR(W → τν) / BR(W → μν) = 0.992 ± 0.013

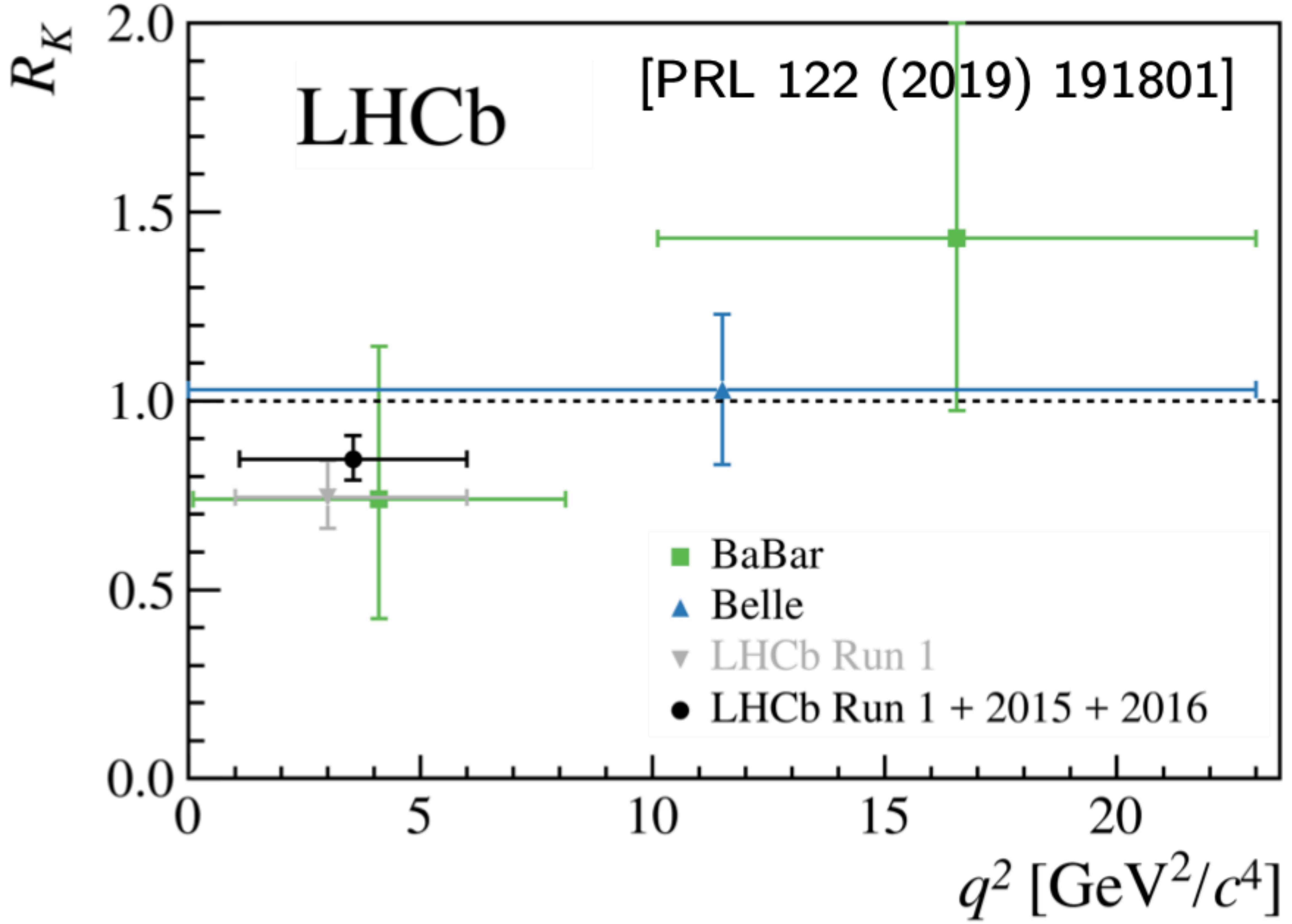
(factor two in precision compared to LEP)

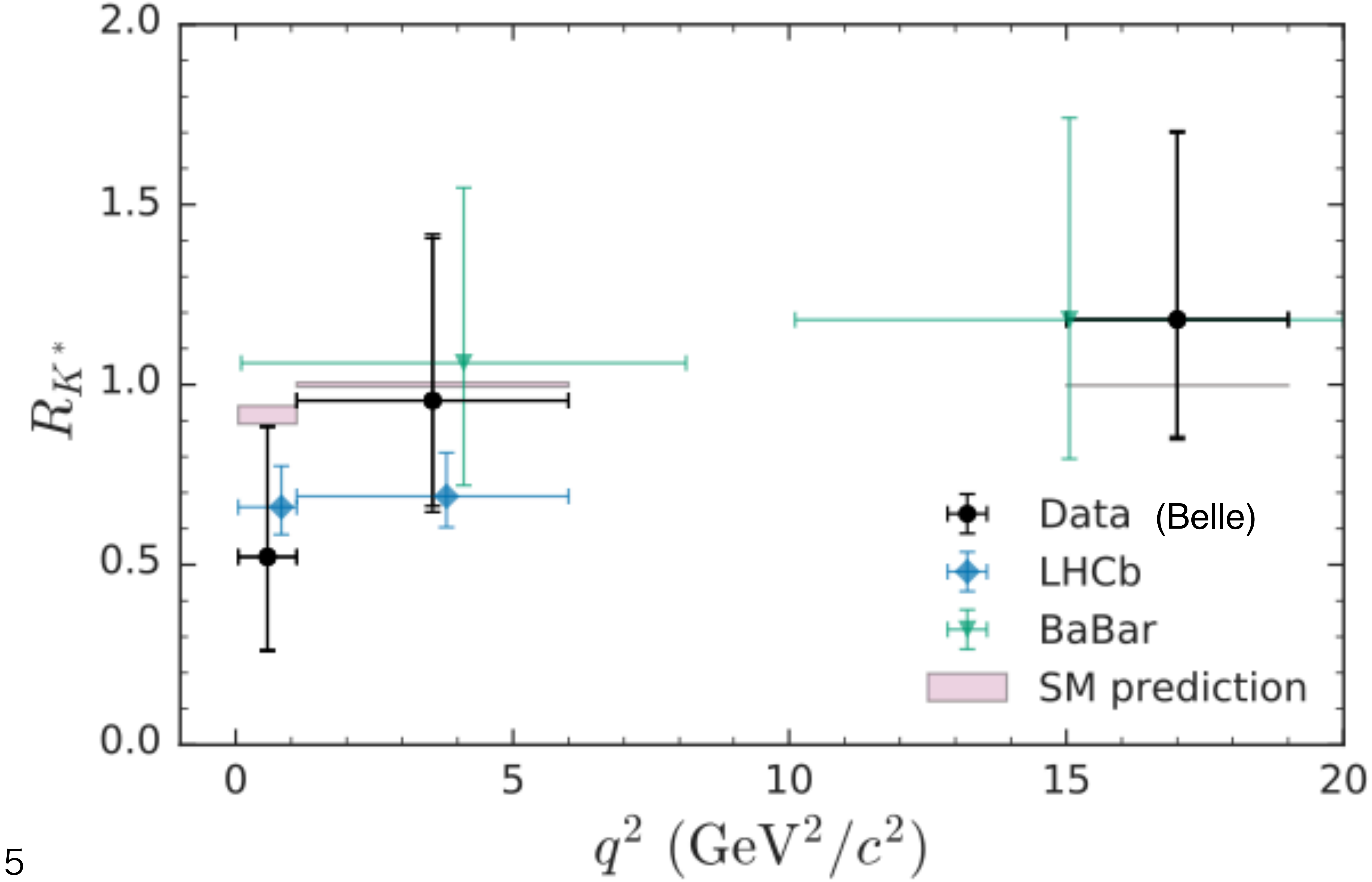
Consistent with Lepton-Flavour Universality

$R_{K^{(*)}}$



- Hints of possible violation of e-μ universality in $B^+ \to K^+l^+l^-$ decays?
  - $R_{K^{(*)}} = BR(B \to K^{(*)}\mu^+\mu^-)/BR(B \to K^{(*)}e^+e^-)$ show deviations from SM by ~ 2.5σ
- $R_{K^+} = 0.846^{+0.060}_{-0.054}(\text{stat.})^{+0.014}_{-0.016}(\text{syst.})$
  - Compatible with SM at 2.5σ



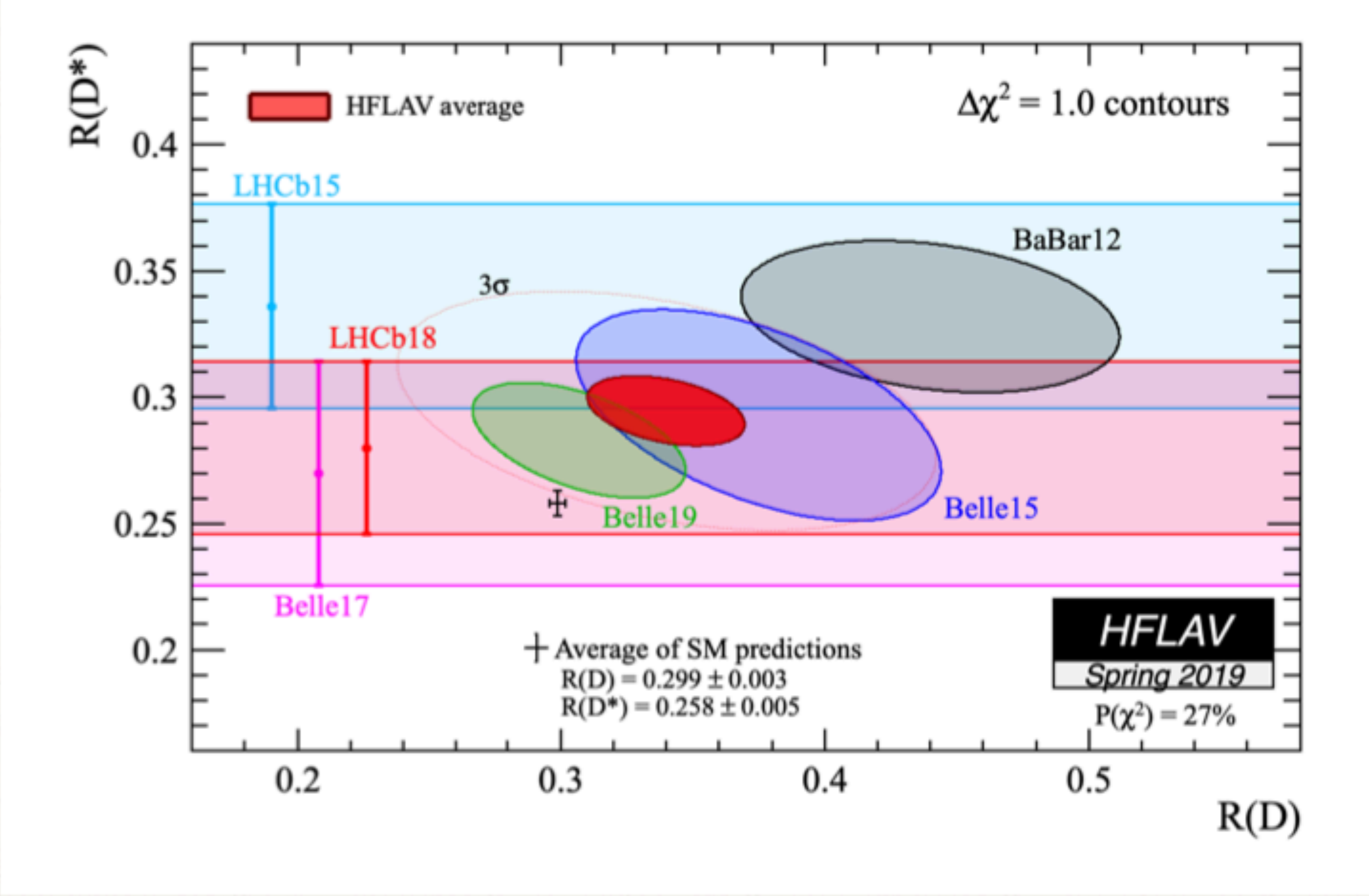


$R_{D(*)}$

$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

- R(D*) may also indicate the possible deviation from SM
- Lepton universality test with τ and e/μ

- Recent Belle data shows closer to SM…but there is a tension with SM at the 3σ level



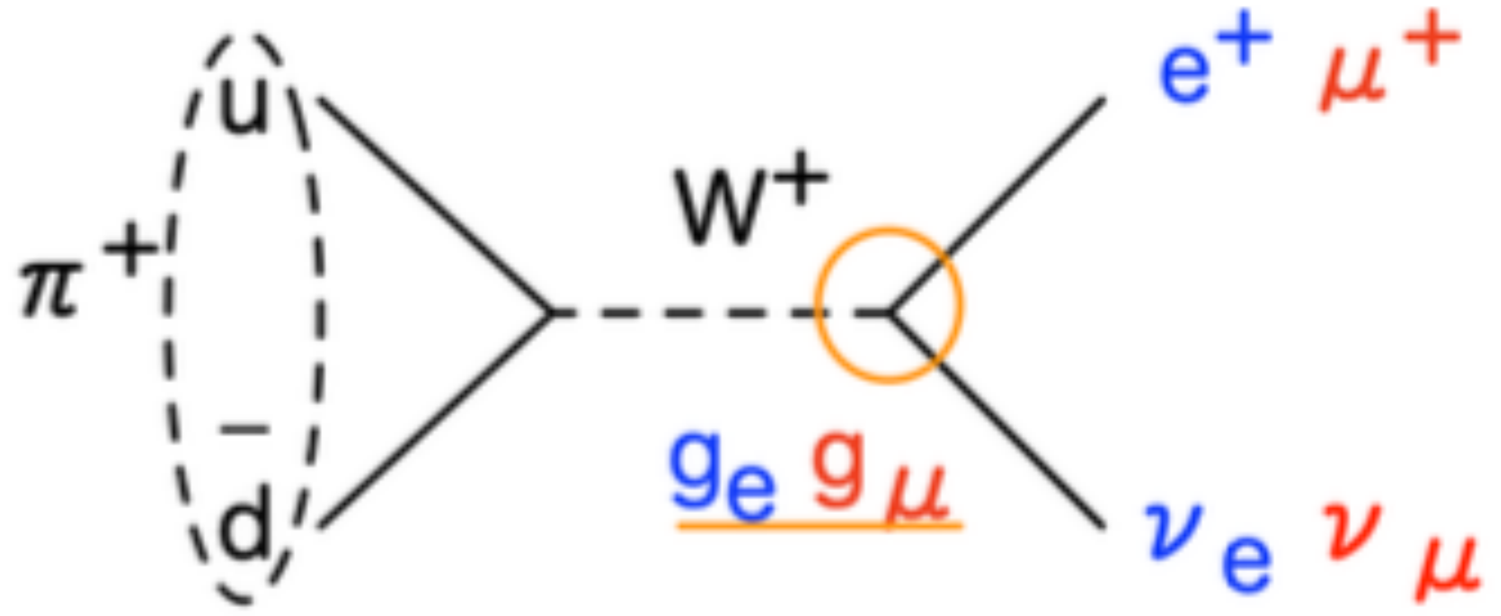
❖ WA combination of R(*D*) and R(*D**) is in tension with SM at the **3.08 σ level**

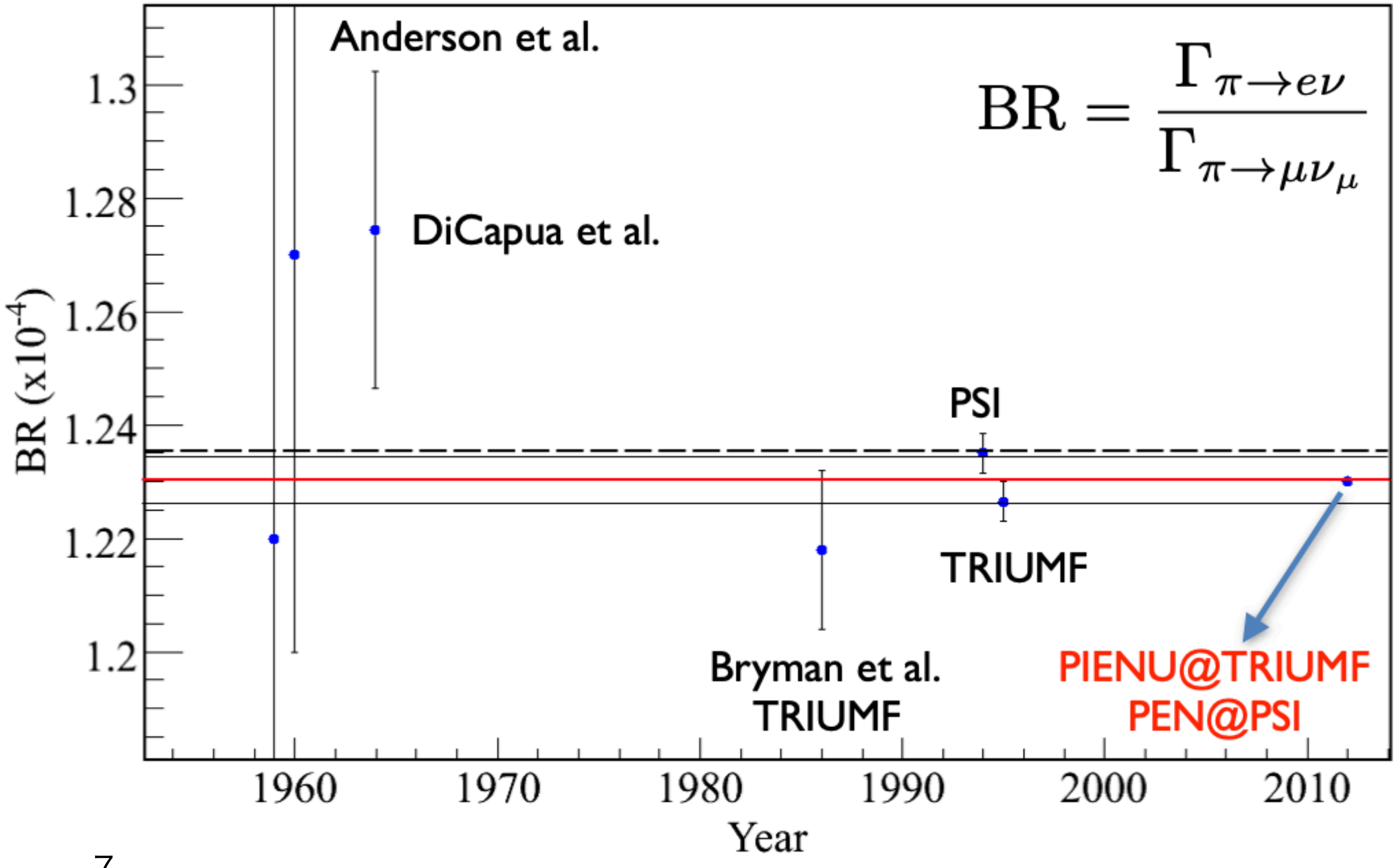
Lepton flavor universality study with π

- $R_{e/\mu} = \Gamma[\pi \rightarrow e\nu(\gamma)] / \Gamma[\pi \rightarrow \mu\nu(\gamma)]$
  - Calculated in the SM with extraordinary precision to be $R^{SM}_{e/\mu}$ = 1.2352±0.0002)×10^{-4}

    0.02%
  - Latest experimental values $R^{exp}_{e/\mu}$ = (1.2344±0.0023(stat)±0.0019(syst))×10^{-4} (PIENU) PRL. 115, 071801 (2015)

    0.2%
  - Sensitivity to new physics beyond the SM up to mass scales of O(500) TeV
  - Examples of new physics : R-parity violating supersymmetry, extra leptons, leptoquarks
  - Future PIENU/PEN will reach < **0.1%**
- Any room for further improvement by the MEG II liquid xenon detector?



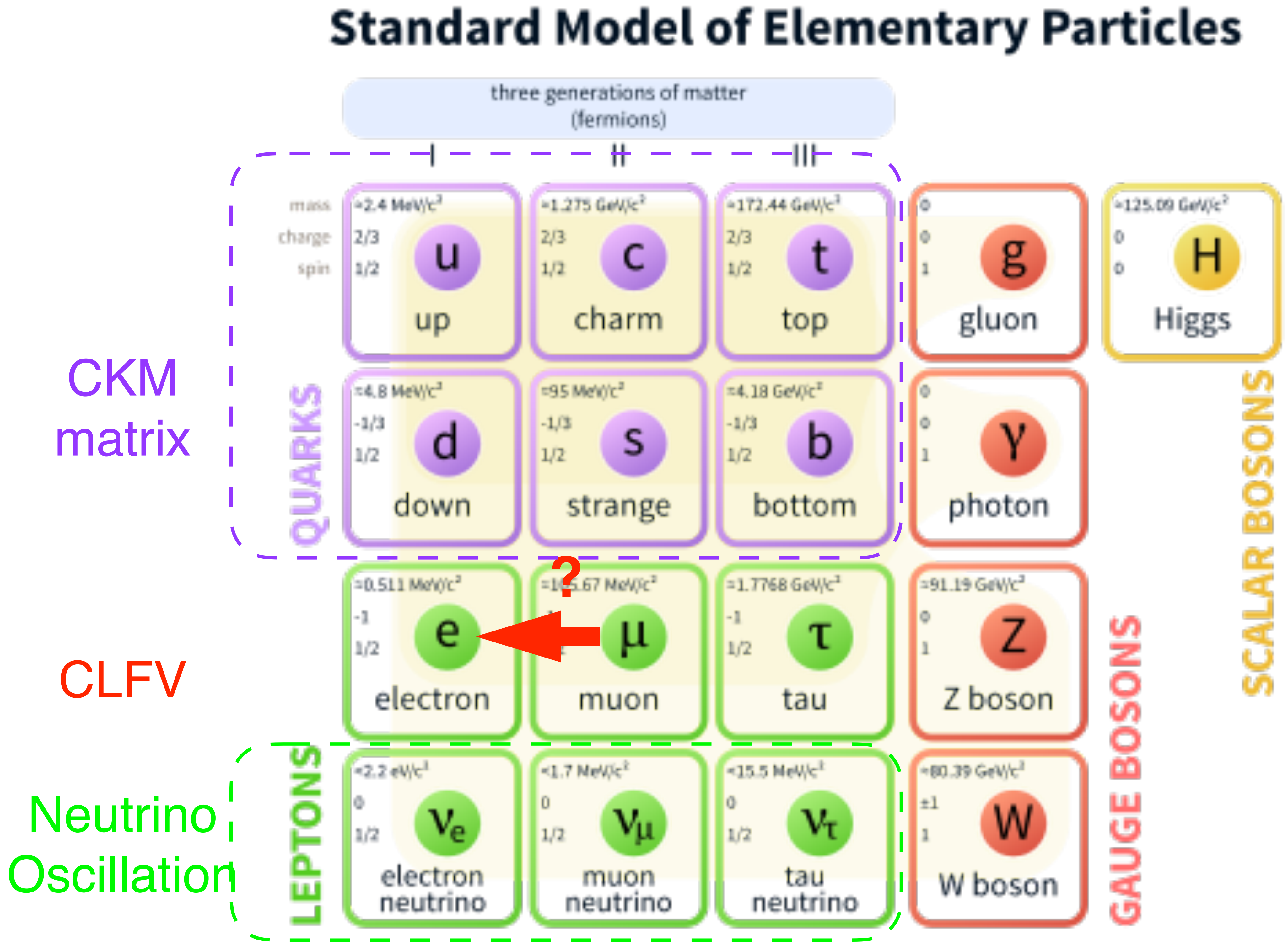


MEG II experiment

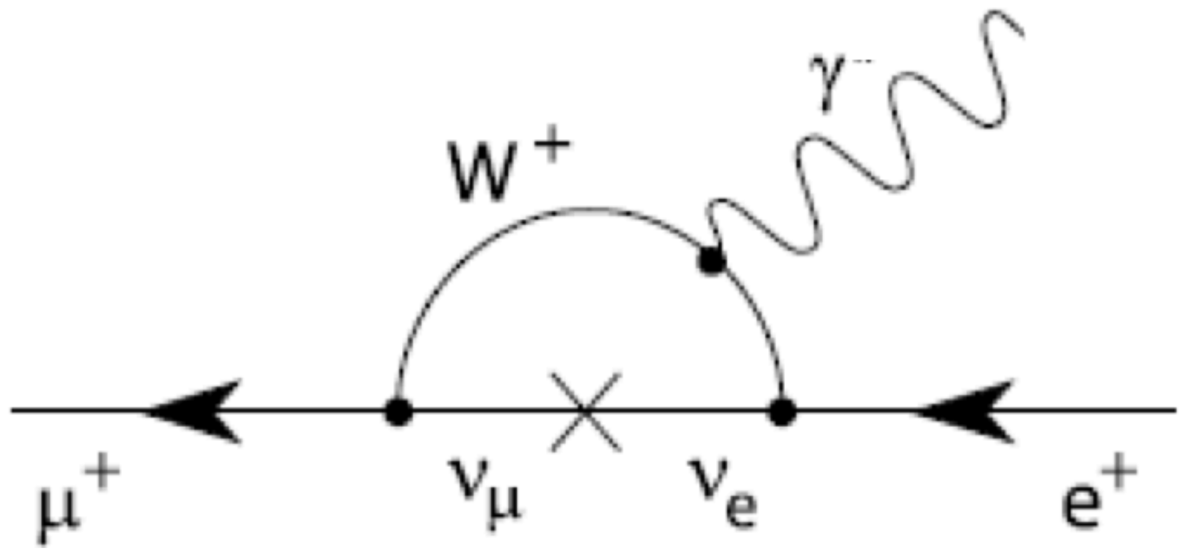
MEG II Motivation (1)

- Charged Lepton Flavor Violation (CLFV) search
  - Flavor violation phenomena already observed in quarks (CKM matrix) and neutral lepton (neutrino oscillation)
  - However, charged lepton flavor violation has never been observed. We don't know the reason yet.

- $\mu \to e\gamma$ decay
  - Suitable mode to look for CLFV decay
  - In standard model with neutrino oscillation, the calculated branching ratio $Br(\mu \to e\gamma) \sim 10^{-54}$
    - no standard model background
  - An observation of CLFV is clear evidence of new physics



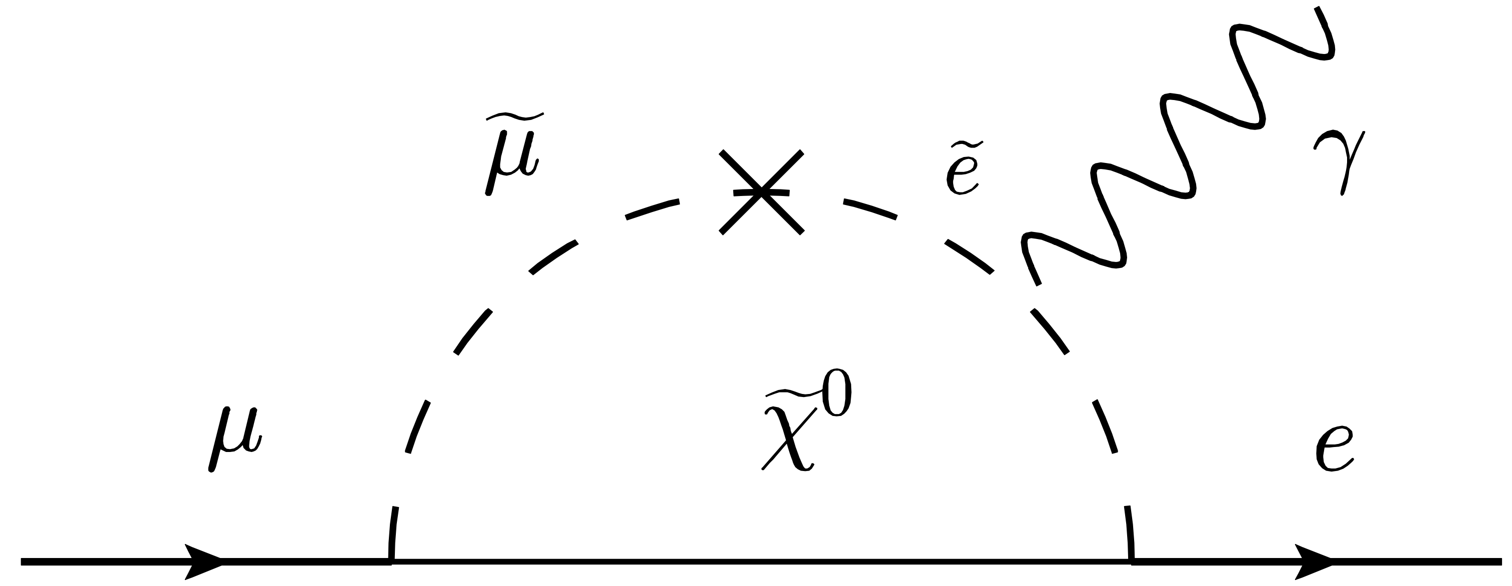
From Wikipedia

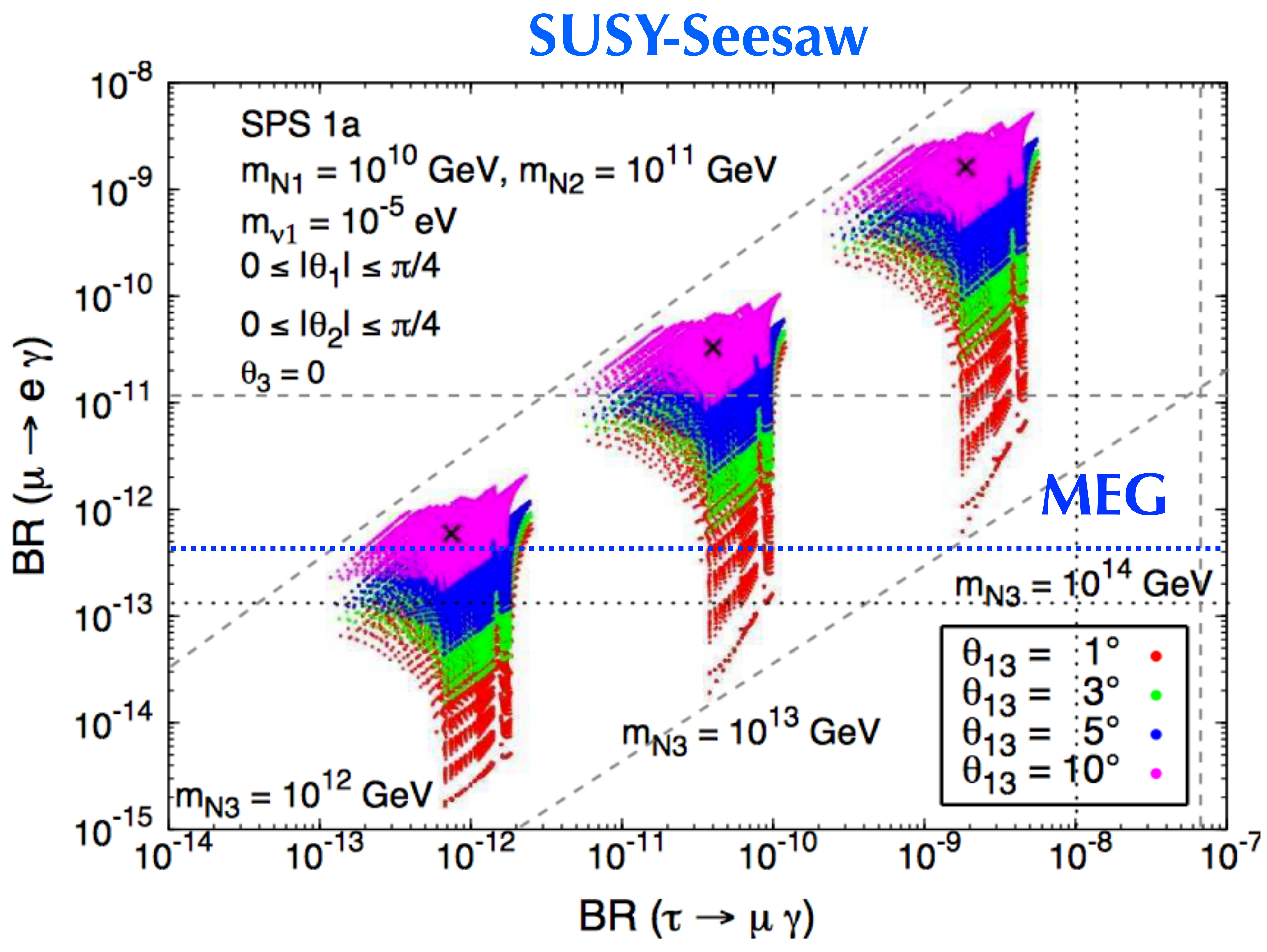


MEG II motivation (2)

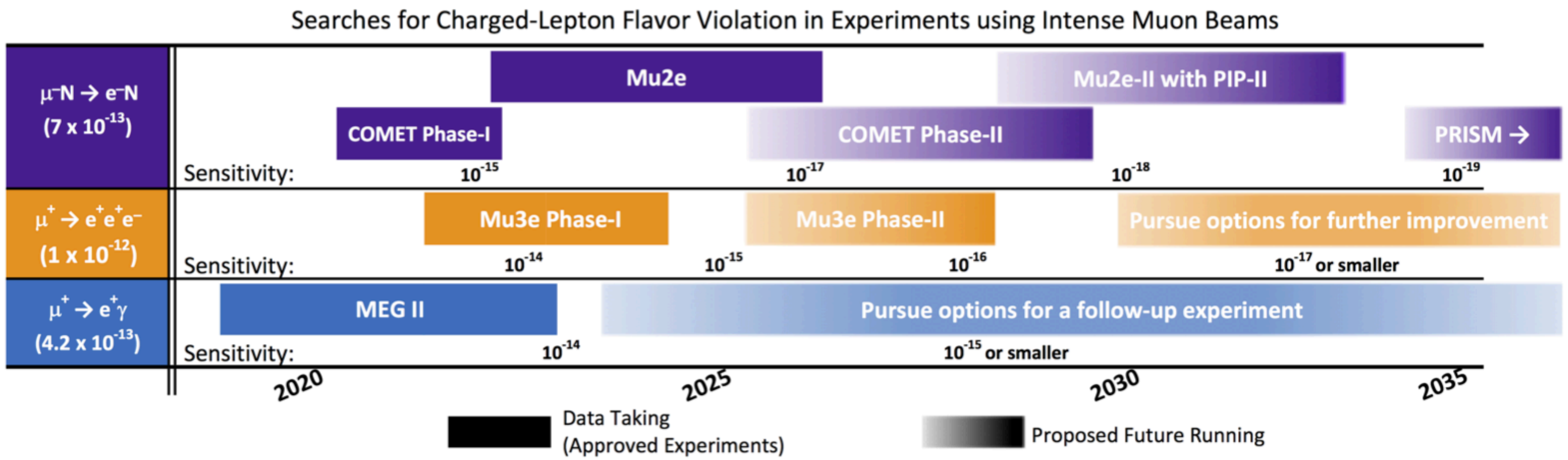
- Many new physics theories such as SUSY-GUT/SUSY-seesaw predict large CLFV
  - CLFV decay can be enhanced by new particles in loop
  - The experimental sensitivity already reaches the new physics prediction region, and we have chances for the discovery

- Many new experiments will start soon
  - μ→eγ at PSI (MEG II)
  - μ→eee at PSI (Mu3e)
  - μN→eN at J-PARC (COMET), at FermiLab (Mu2e)
  - Complementary to pin down the new physics behind





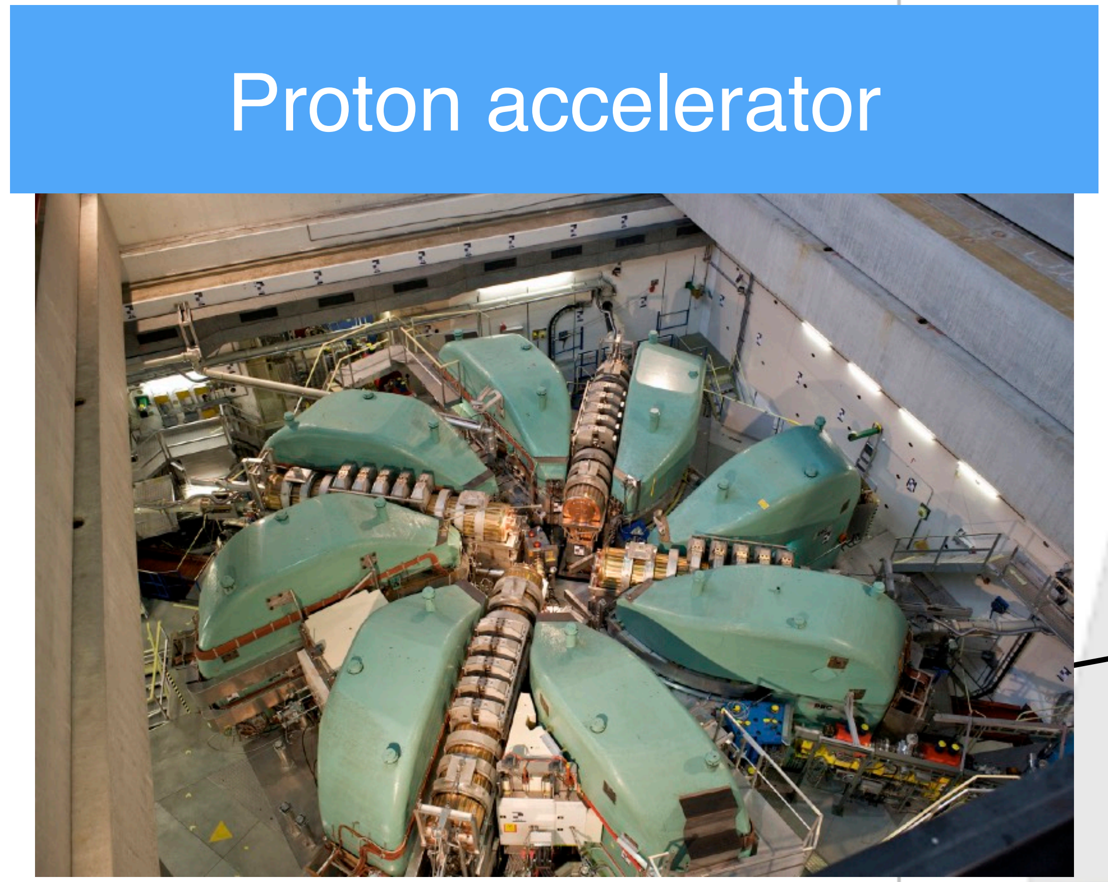
S. Antusch et al, JHEP 0611:090(2006)

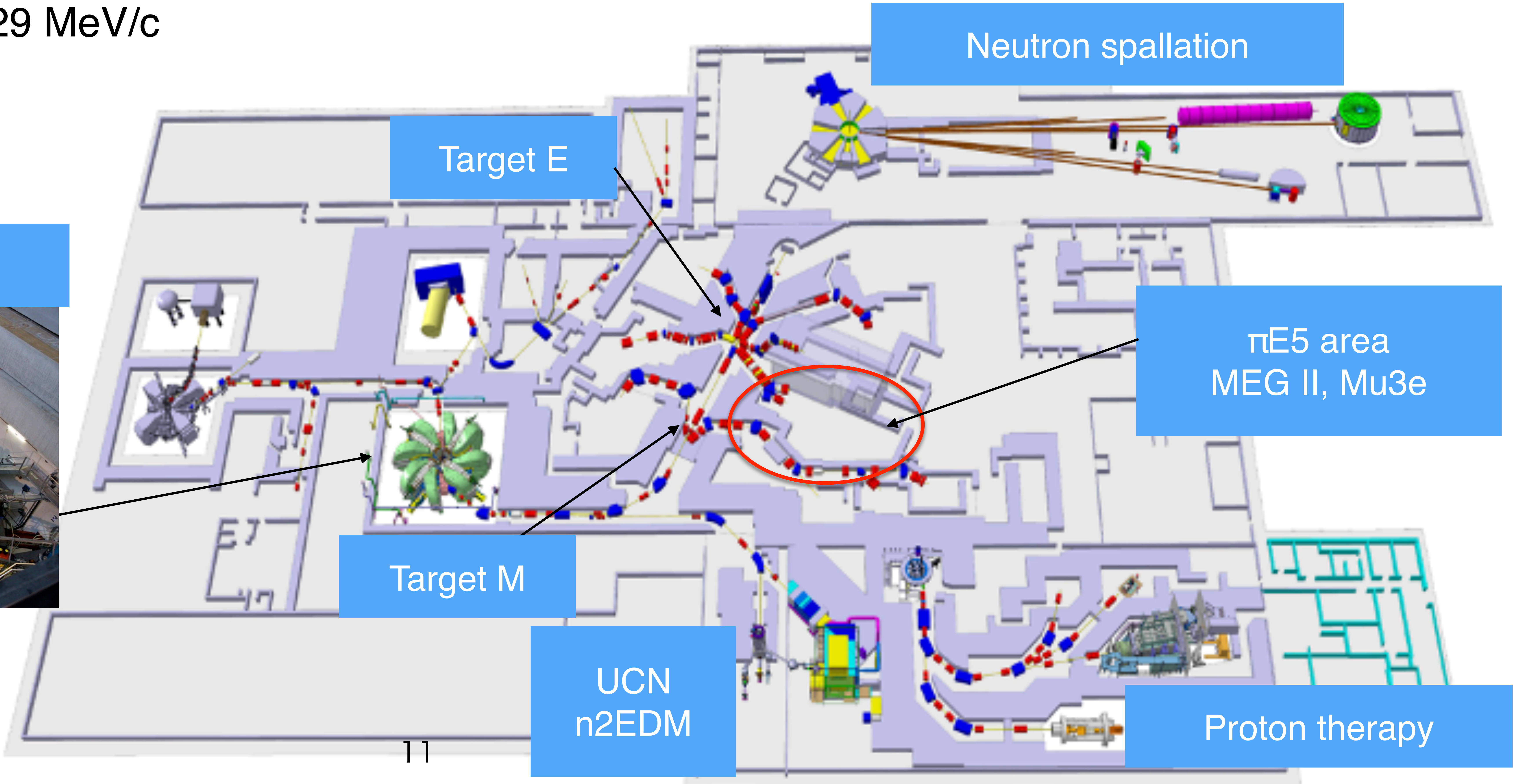


PSI DC muon beam

Andreas KNECHT

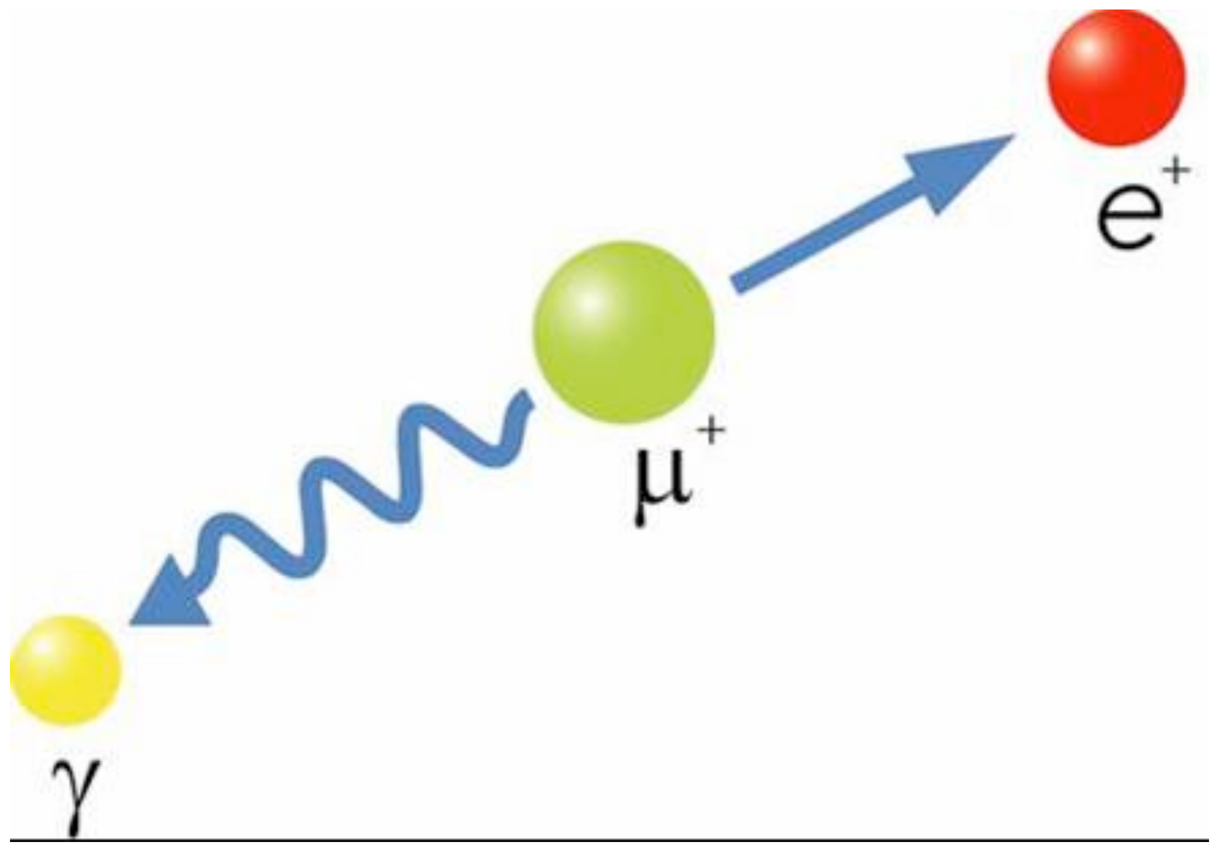
- Paul Scherrer Institute in Switzerland
  - 590 MeV 2.4mA proton ring cyclotron
  - World most intense DC muon beam > 10^8 μ/s
  - 50 MHz RF time structure << μ lifetime ~ 2μs
    - No time structure in muon decay (continuous)
  - Surface muon beam ~ 29 MeV/c





$\mu \rightarrow e\gamma$ signal and background

Signal

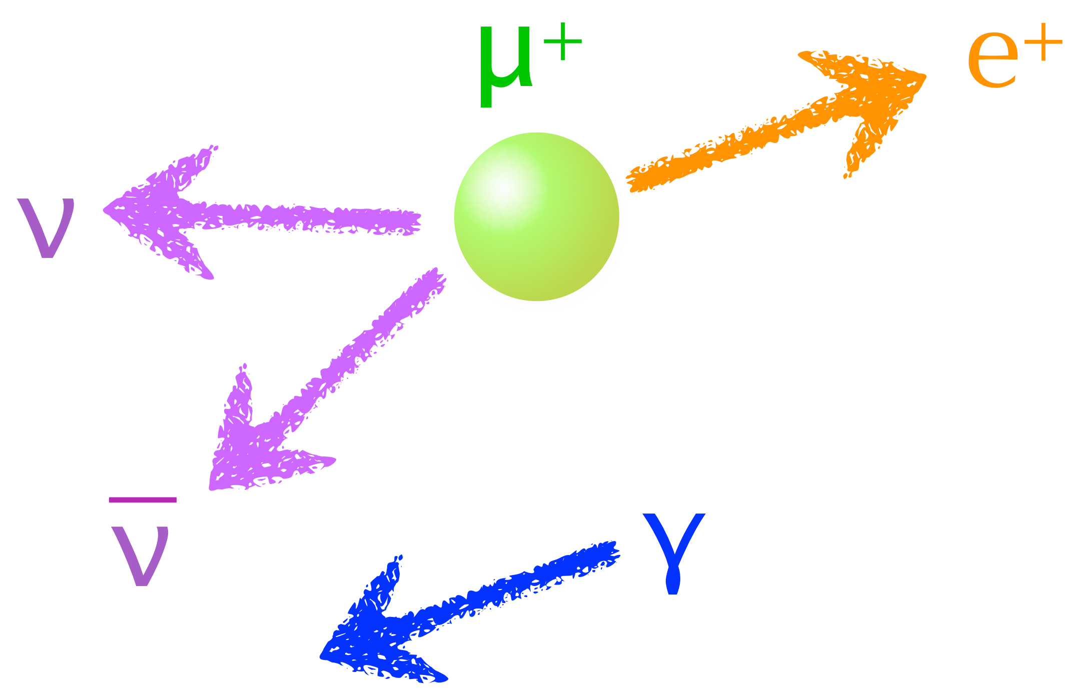


$E_\gamma, E_e \simeq 52.8$MeV
$\Theta_{e\gamma}=180°$, $T_\gamma=T_e$

Background

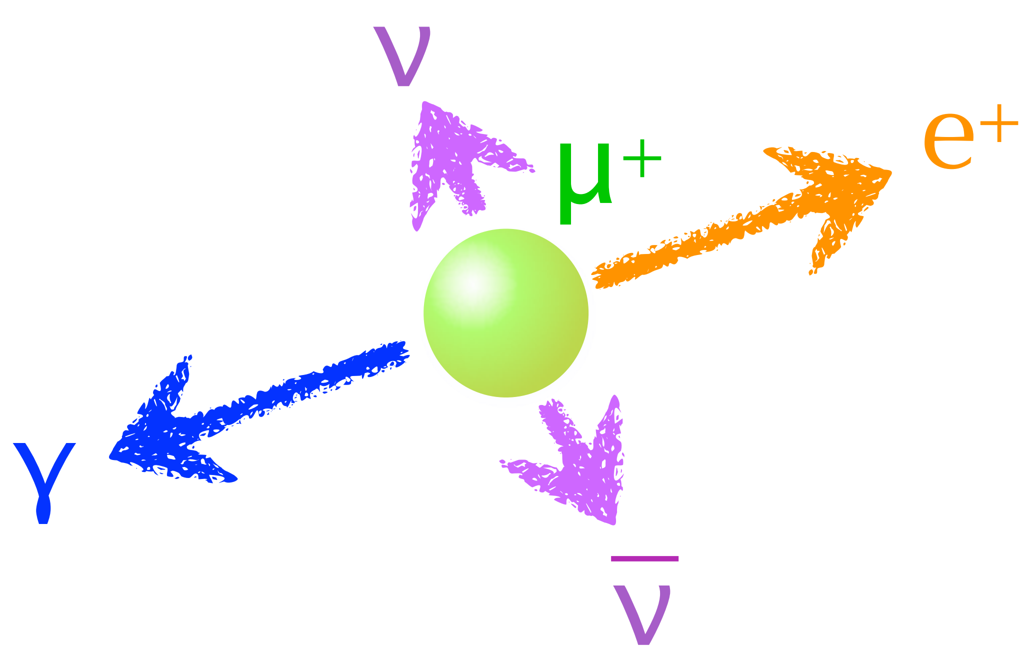
Accidental

Dominant BG



Michel e^+ + random γ from RMD/Annihilation in flight (AIF)

Radiative Muon Decay

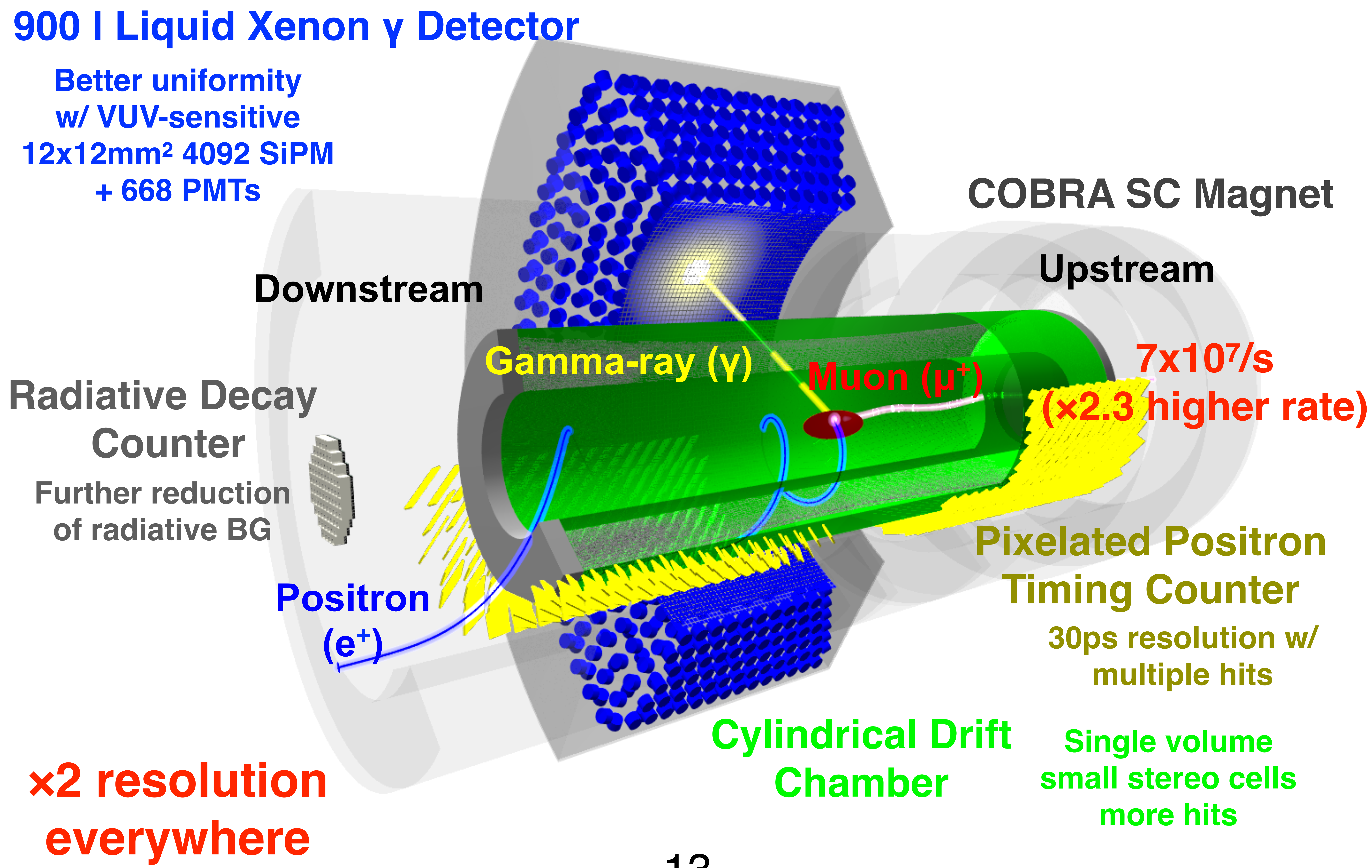


e^+-γ timing coincident

$$N_{acc} \propto (R_\mu)^2 \times (\Delta E_\gamma)^2 \times \Delta E_e \times (\Delta\Theta_{e\gamma})^2 \times \Delta t_{e\gamma} \times T$$

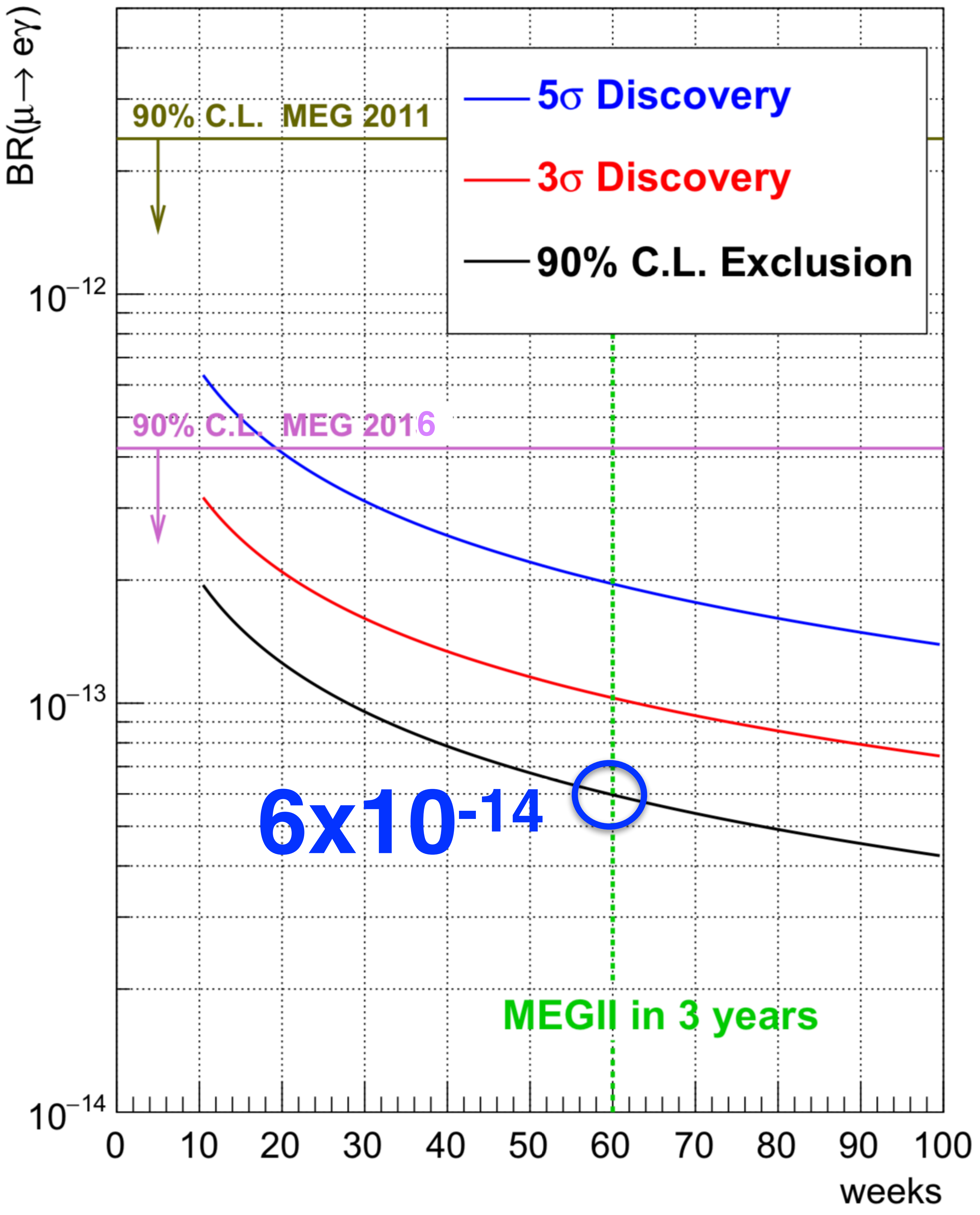
- Lower instantaneous muon beam rate (DC muon beam)
- Better detector resolutions

MEG II Experiment



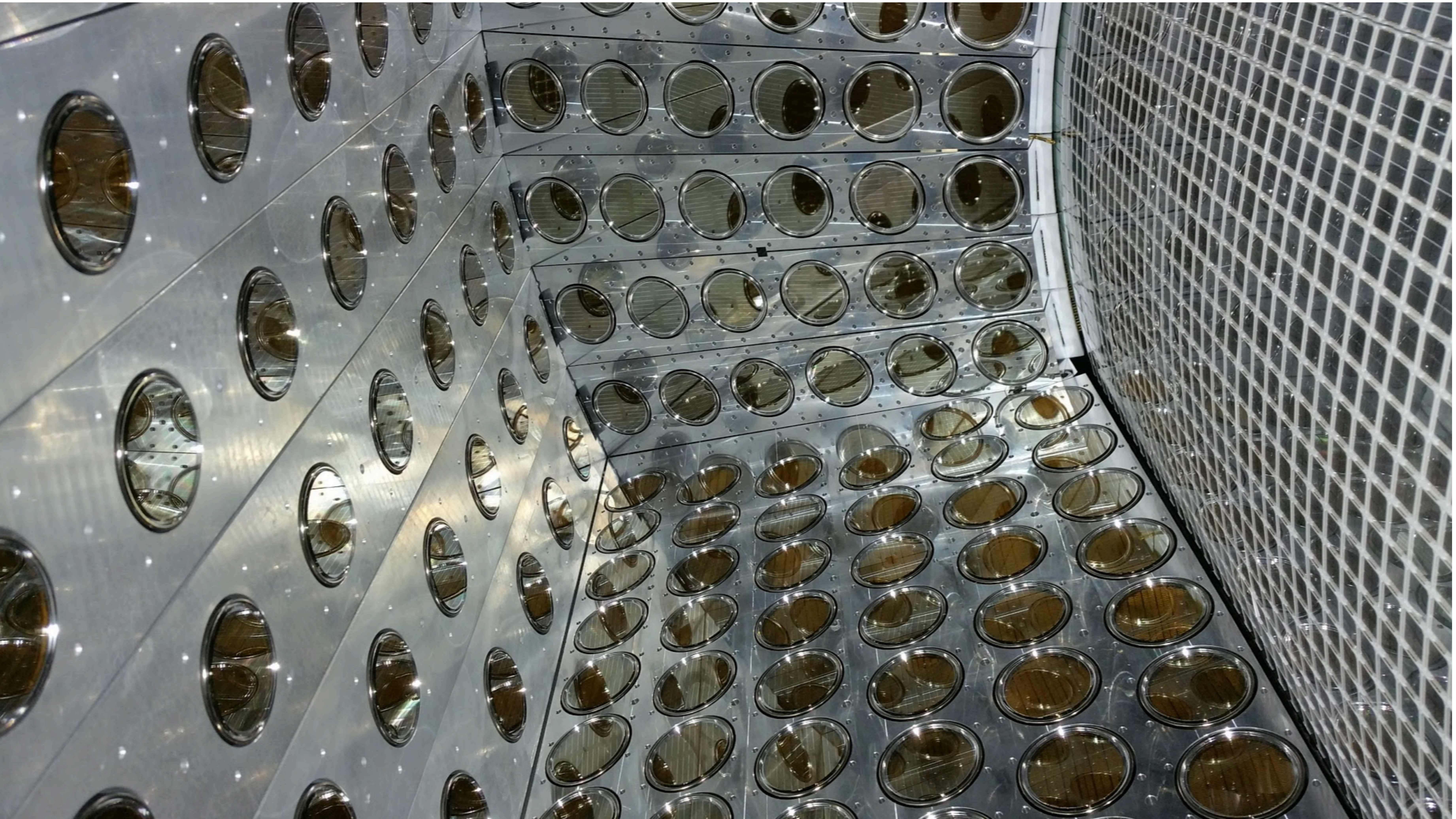
Sensitivity

Resolution	MEG	MEG II
E_{e+} (keV)	380	130
θ_{e+} (mrad)	9.4	5.3
ϕ_{e+} (mrad)	8.7	3.7
z_{e+}/y_{e+} (mm) core	2.4/1.2	1.6/0.7
E_γ(%) (w>2cm/<2cm)	1.7/2.4	1.0/1.1
u_γ, v_γ, w_γ (mm)	5/5/6	2.6/2.2/5
$t_{e\gamma}$ (ps)	122	84
Efficiency (%)		
Trigger	99	99
γ	63	69
e^+ (tracking × matching)	30	70



- Data for a few months exceed the current limit, and reach 6×10^{-14} in three years
- Engineering run followed by physics run from 2021

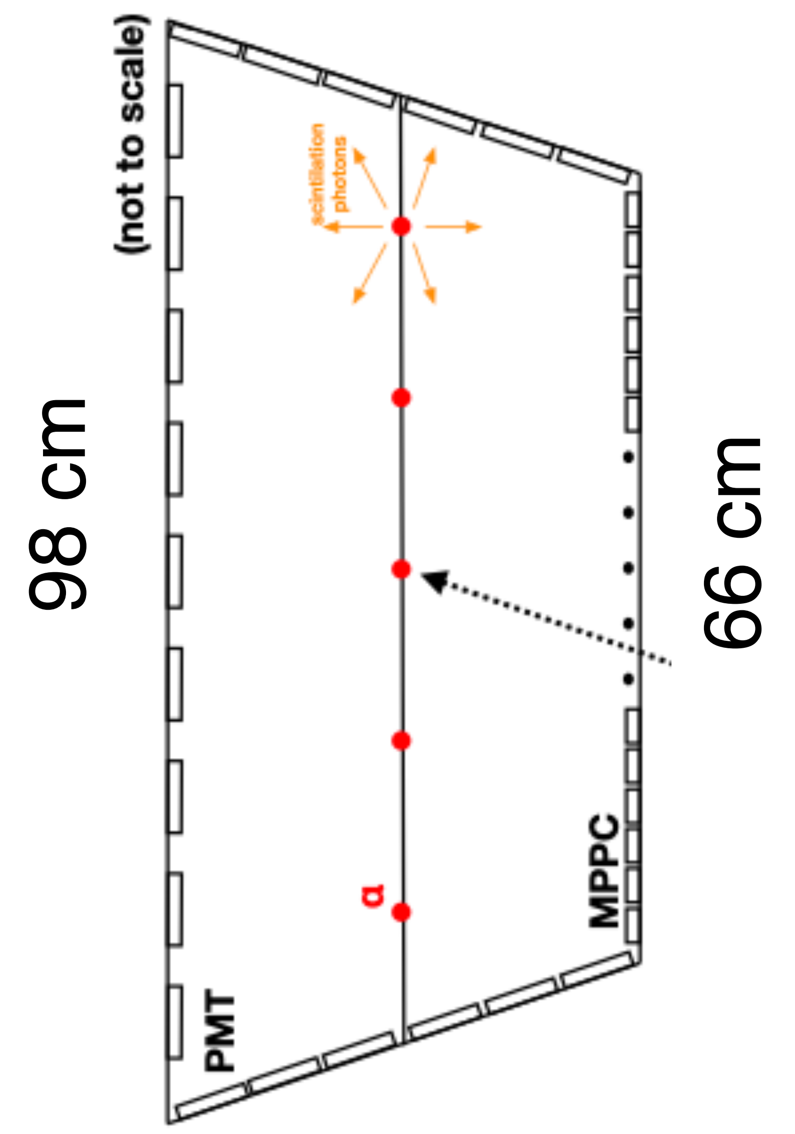
MEG II Liquid Xenon Detector



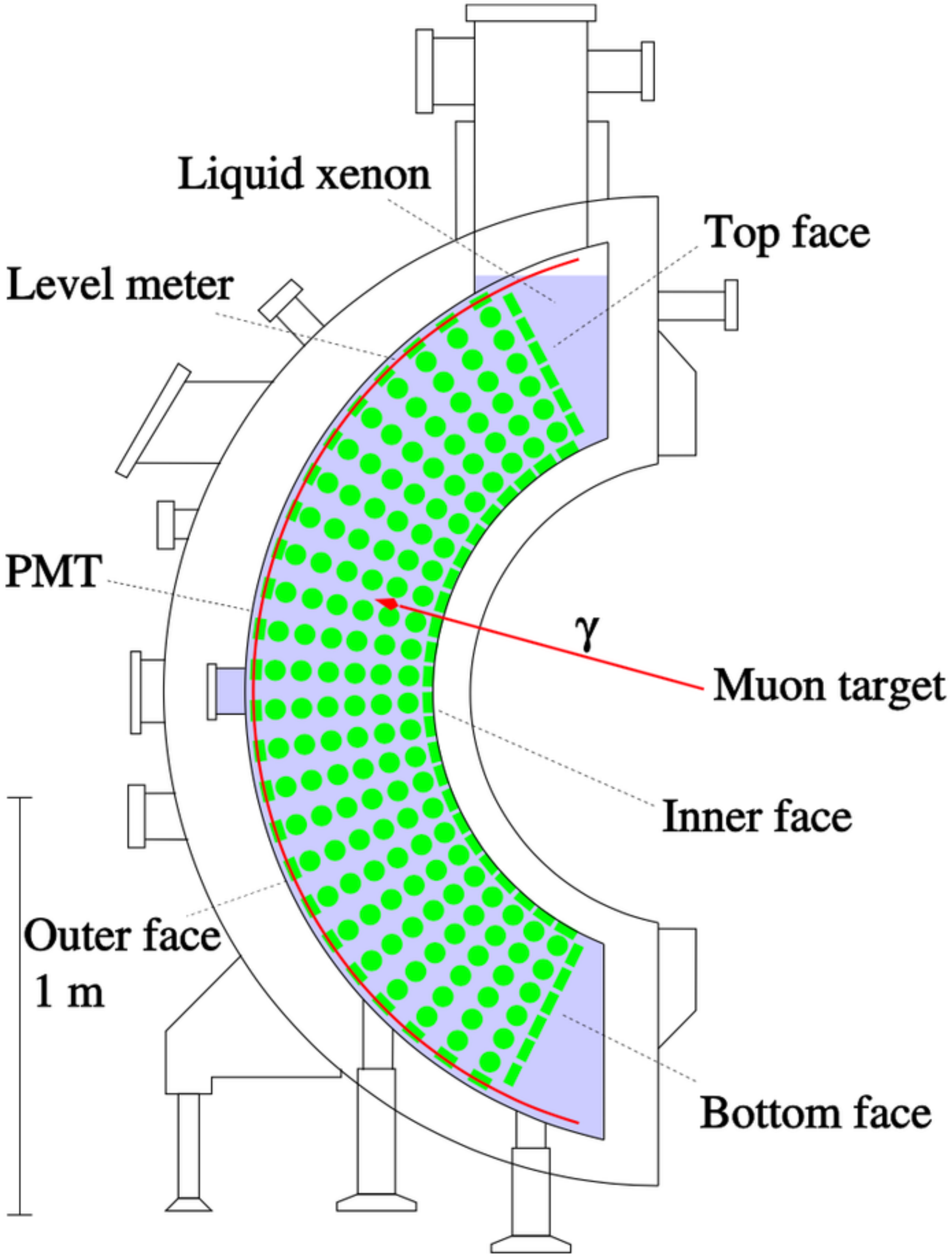
MEG II Liquid Xenon Detector

- Position, timing, energy measurements of 52.8 MeV γ from μ→eγ decay
  - C-shape to fit the cylindrical shape of the superconducting magnets
  - Thin entrance window for γ (honeycomb structure) : $0.075X_0$
    - 66 cm (horizontal) × 140 cm (arc)
  - Vacuum vessel to keep LXe at 165K
- Detector medium : 900 l LXe
  - Homogeneous
  - Heavy (3 g/cm^3)
  - High light yield
  - decay time : 45ns (γ)
  - Depth 38.5cm (~$13X_0$)
- Scintillation readout : 4092 MPPC ($15\times15mm^2$) + 668 PMTs (51mmϕ)
  - immersed in LXe ($0.029X_0$ from MPPC)
  - Sensitive to VUV-light (175nm)
  - Operational at 165K
  - All the waveforms are recorded by WaveDREAM (DRS4)

Top view

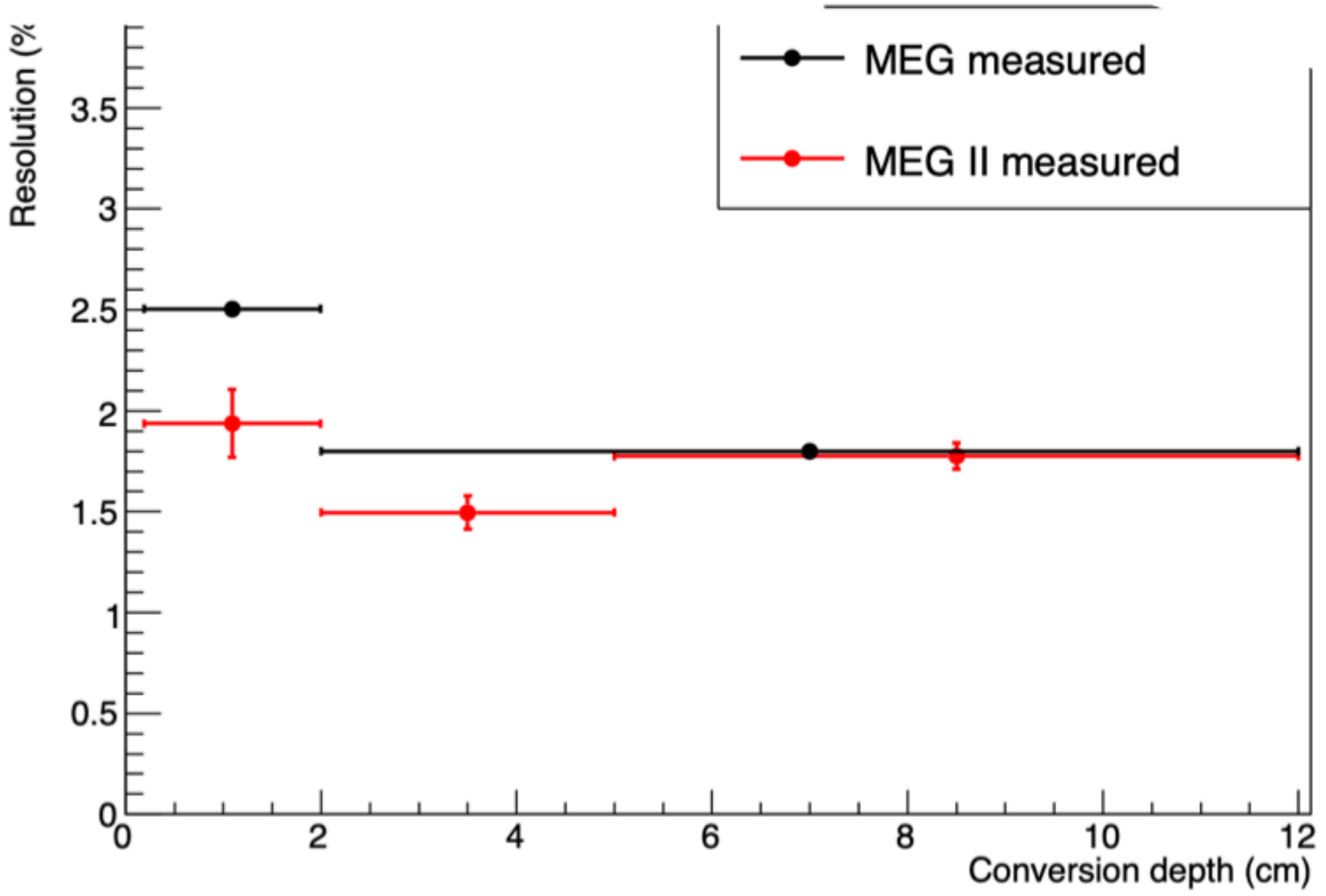


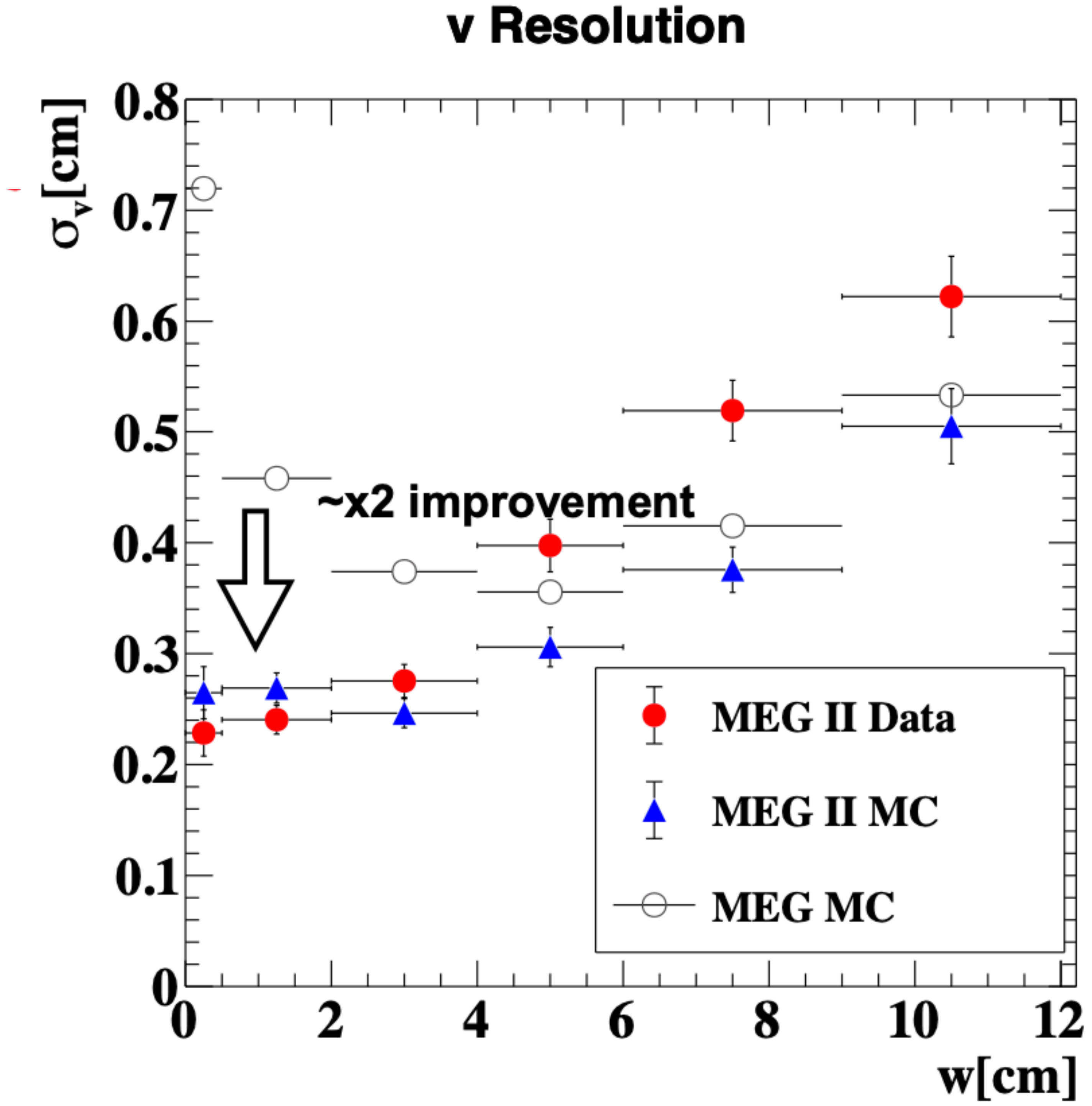
Side view



The LXe detector commissioning

Energy resolution
(for 53MeV γ) vs depth





- Energy, position, timing resolutions are begin evaluated
- The resolutions near the signal region will be evaluated by $\pi^- p \rightarrow \pi^0 n$, $\pi^0 \rightarrow 2\gamma$ run in this November
- Full electronics ready early next year, and start engineering run in 2021.
- Three years physics run is planned after that.

	MEG (measured)	MEG II (design)	
position resolution $(u/v/w)$(mm)	5/5/6	2.6/2.2/5	~2.5mm
energy resolution (%)($w < 2\,\mathrm{cm}/w > 2\,\mathrm{cm}$)	2.4/1.8	1.1/1.0	~1.7%
timing resolution (ps)	62	76	~55ps
efficiency (%)	63	69	

New idea for LFUV measurement

PIENU Detector

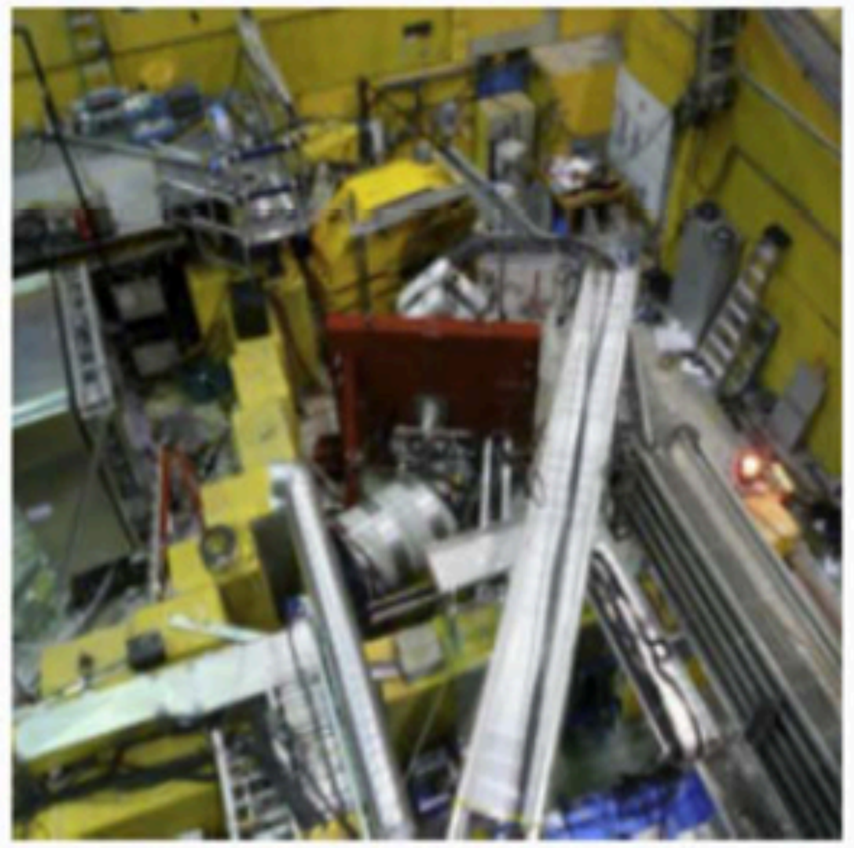
Sullivan TRISTAN

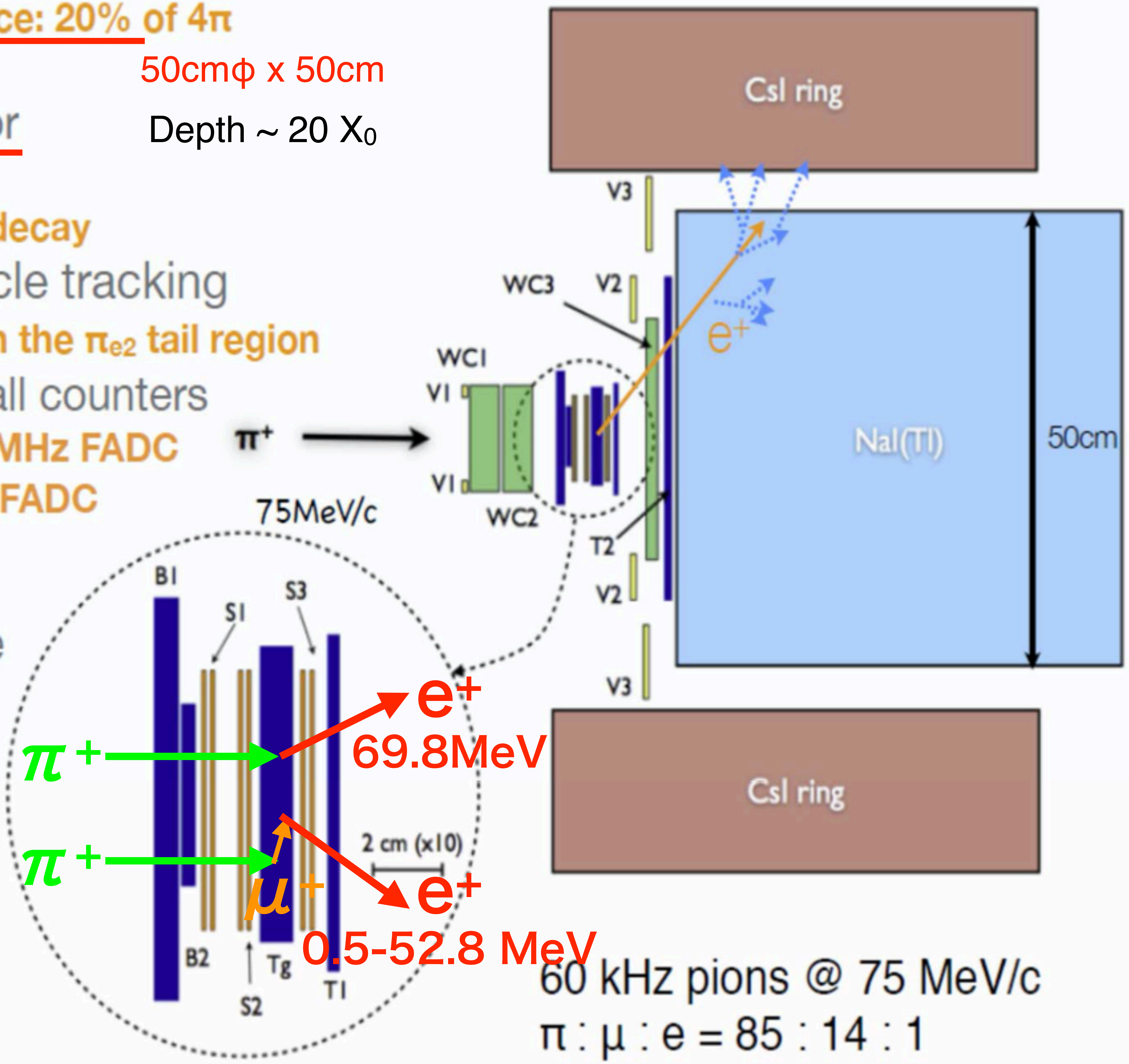
- Single crystal NaI(Tl) right behind the target
  - Geometrical Acceptance: 20% of 4π
  - ΔE = 2.2%(FWHM)
- CsI ring shower collector
  - π_{e2} tail suppression
  - gamma from radiative decay
- SSD and WC for particle tracking
  - Identify π-DIF events in the π_{e2} tail region
- Flash-ADC readout for all counters
  - Plastic Scintillator: 500MHz FADC
  - NaI(Tl) and CsI: 60MHz FADC
  - Pile-up tagging

50cmϕ x 50cm

Depth ~ 20 X_0

- TRIUMF M13 beamline





60 kHz pions @ 75 MeV/c

π : μ : e = 85 : 14 : 1

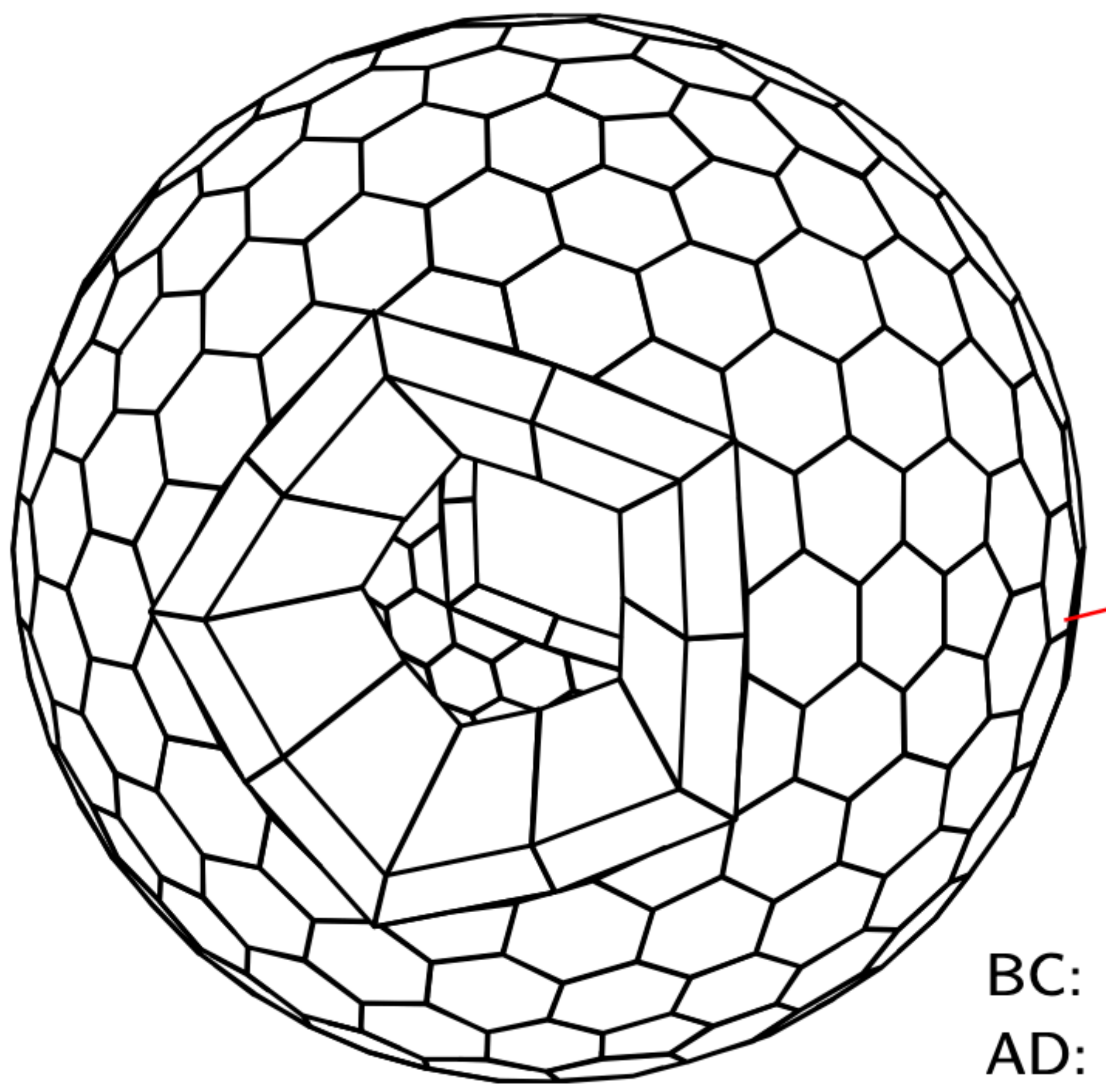
The PEN/PIBETA apparatus

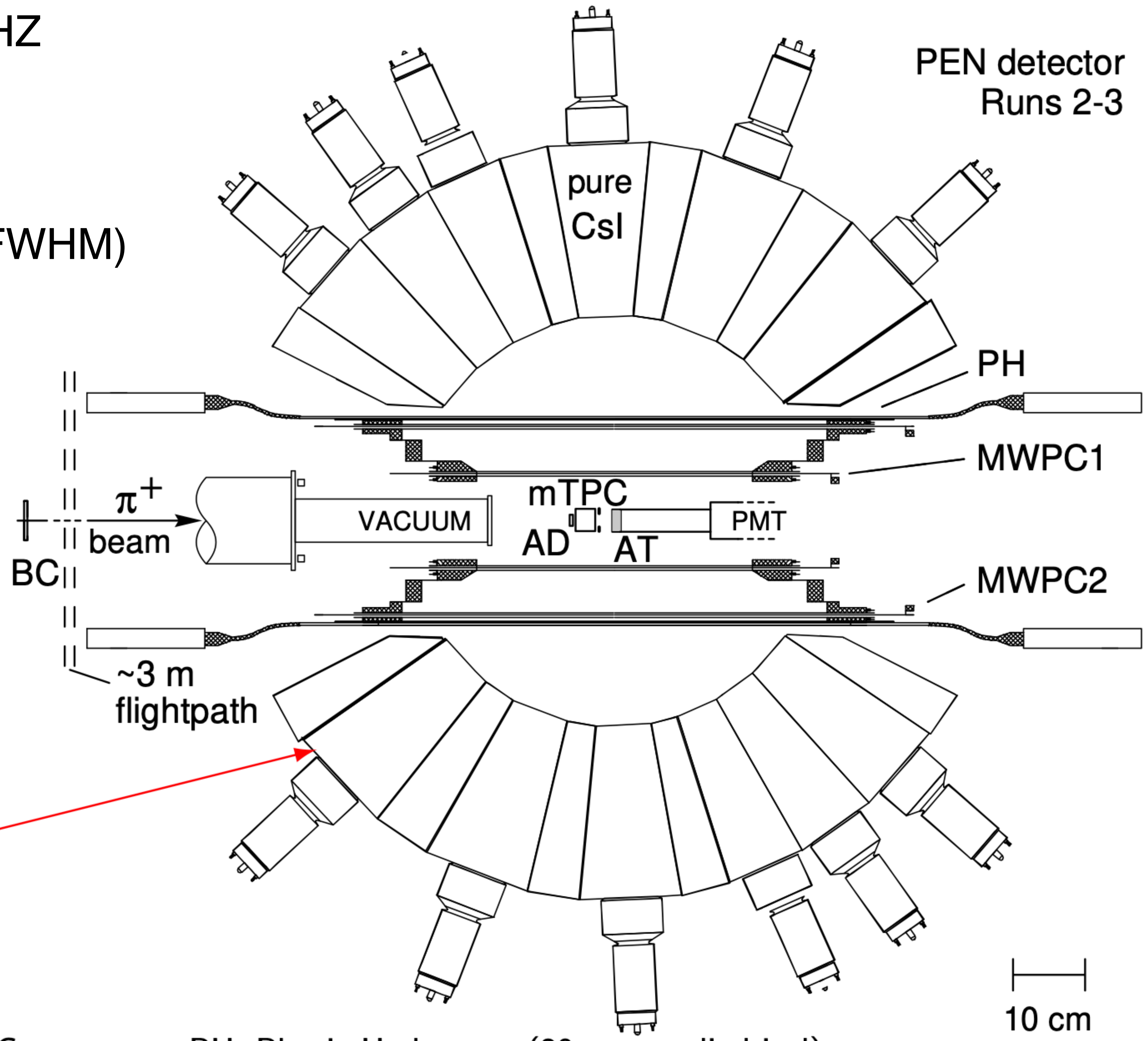
Dinko POCANIC

- πE1 beamline at PSI
- stopped π^+ beam :10-50 kHZ
- active target counter
- 240 module spherical pure CsI calorimeter 6%(FWHM)
- central tracking
- beam tracking
- digitized waveforms

Acceptance ~3π

Depth ~ $12X_0$





BC: Beam Counter
AD: Active Degrader
AT: Active Target

PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)
mTPC: mini-Time Projection Chamber

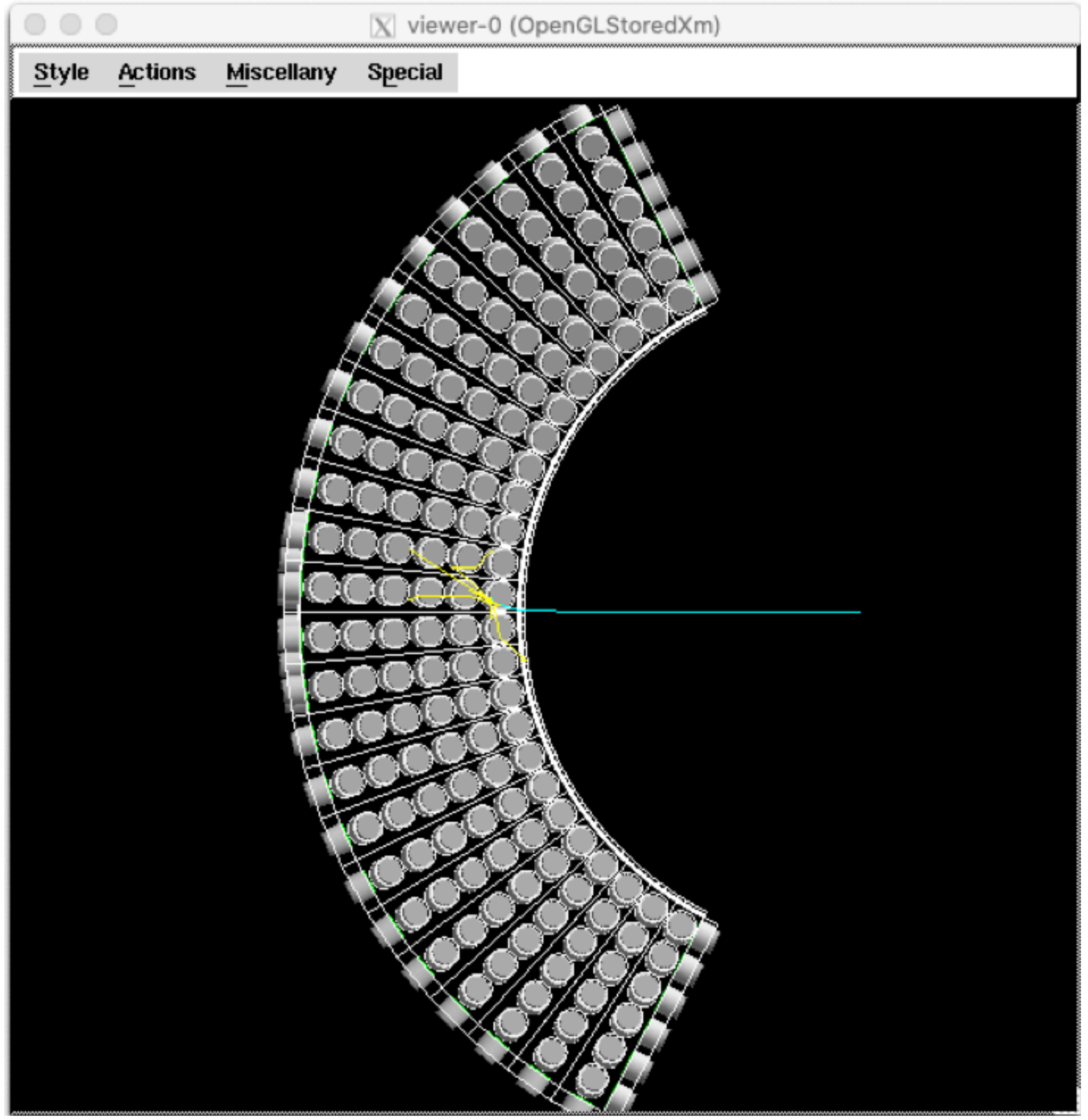
Items for improvements

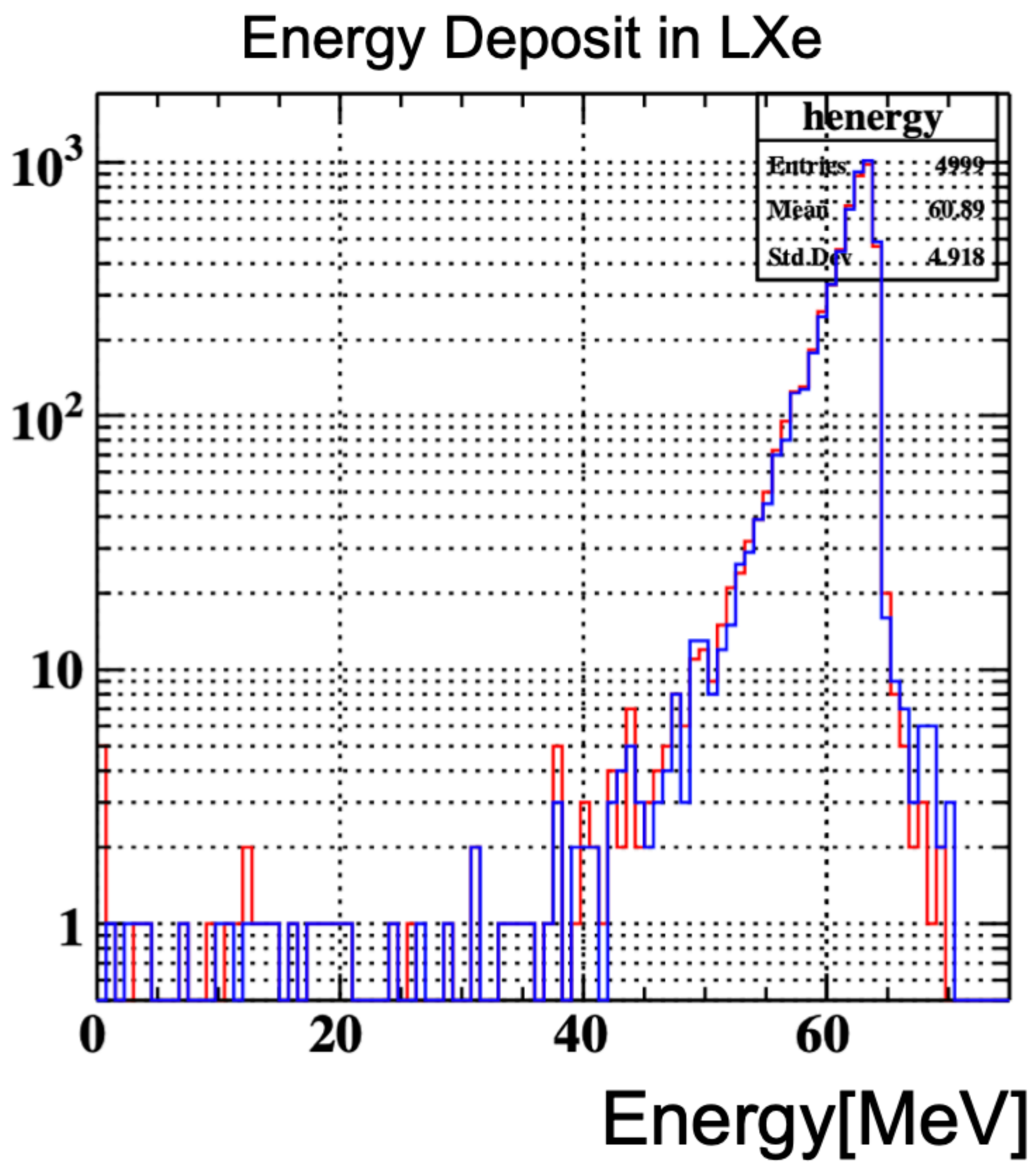
- Goal
  - To reach the same sensitivity as the theory ~ 0.01%
- Statistics
  - 1-2 orders of magnitude improvement necessary
    - PIENU, PEN : 10^7 $\pi^+ \to e^+ \nu$ collected
  - Increase the beam intensity, acceptance
    - Several 10^4 π^+/s → > several 10^5 π^+/s
    - Target region as close as possible in front of calorimeter, large calorimeter

- Systematics
  - One order of magnitude improvement necessary
  - complete containment of EM showers
  - Highly uniform response, depth of the total absorption LXe calorimeter
  - Determination of the “tail” region-of-interest (photo-nuclear radiative effects)

MEG II LXe detector for LFUV experiment

- Quick realization
  - No need for R&D time, no extra cost
  - Right after the MEG II finishes, we can start (or even some studies are possible from now on)
- High performance
  - Fast response (decay time 45ns) → high rate is possible (>10^5 π^+/s)
  - Homogeneous detector
  - Large entrance window
- 69.3 MeV e^+ simulation into the LXe detector (we are setting up…)
  - We need to check the energy response, acceptance, etc.

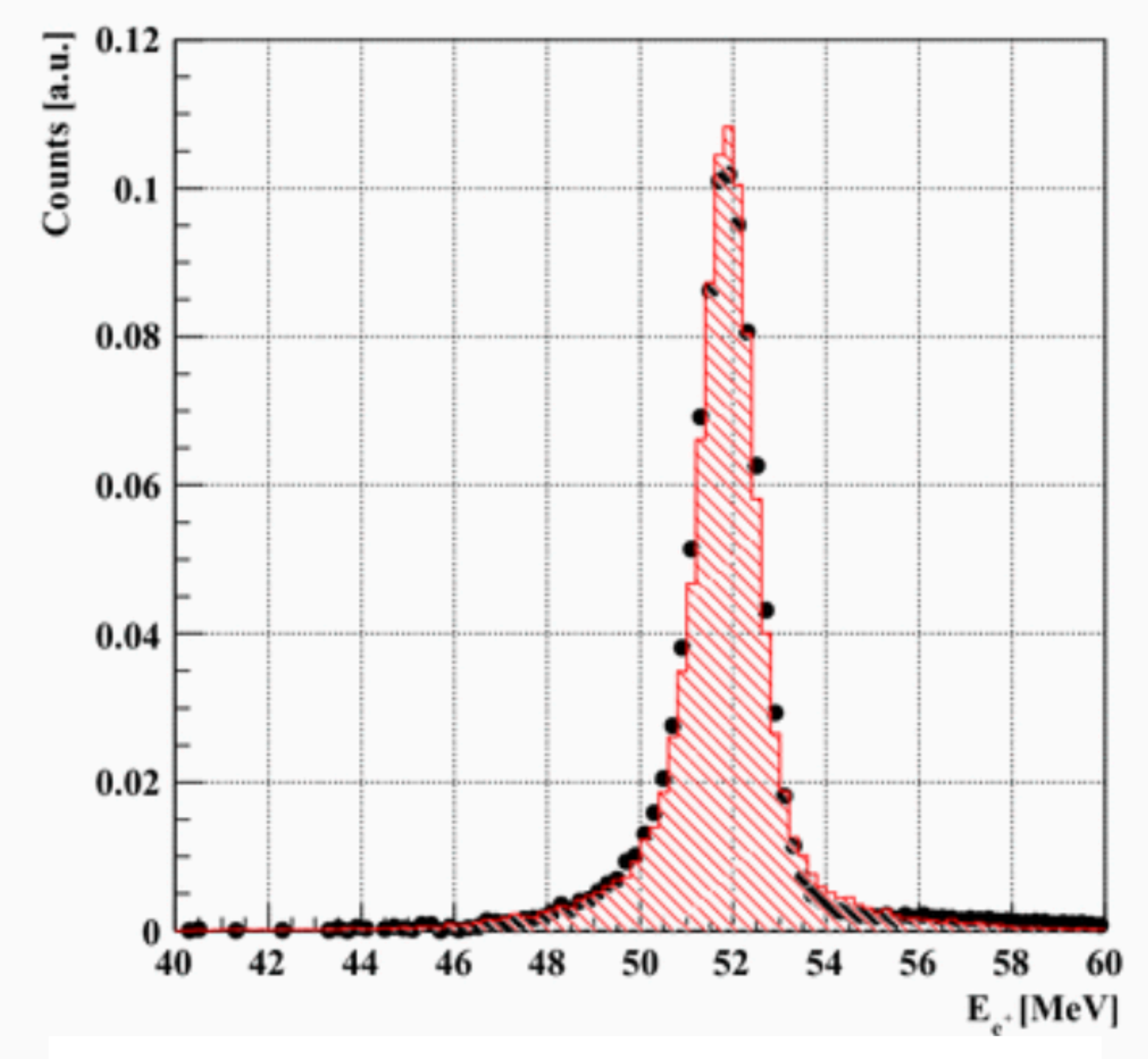




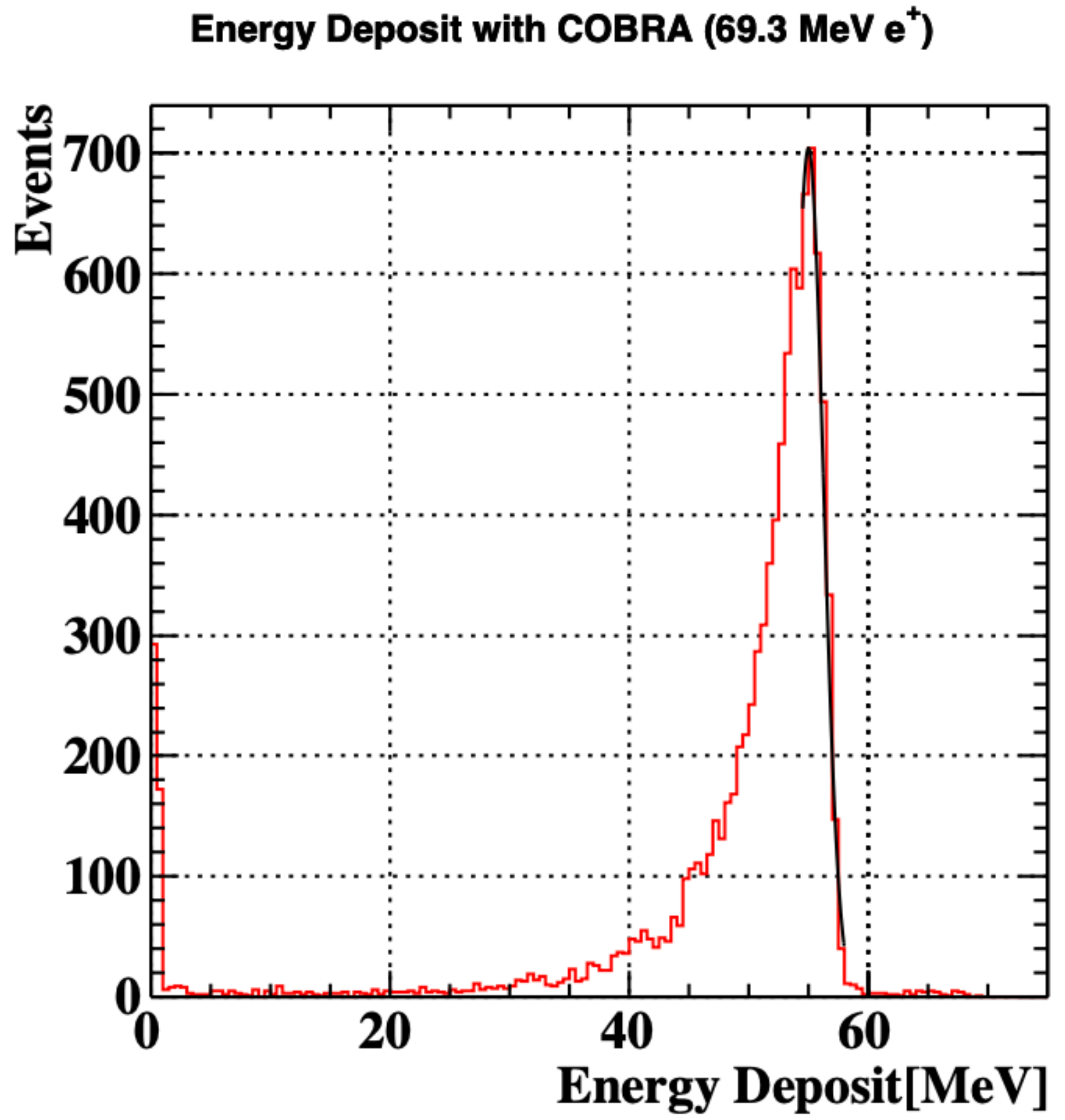
What we want to check with simulation

- LXe detector response to 69.8MeV e^+, 0.5-52.8MeV e^+
  - Positron beam into the center of the LXe detector
  - If we use Mott scattering events, we may be able to demonstrate it with data (Material from Magnets ~ $0.197X_0$)
- LXe detector acceptance for positron detection
  - Detection efficiency for isotropically distributed e^+ generated at the target
- Maximum event rates
  - Energy spectra with pileups at different beam rates
  - Any other constraints?
- Beam test with large prototype or directly with the LXe detector?
  - Test of the photo nuclear effect with LXe by monochromatic Mott scattering events
- Optimization of the detectors around the target
  - π^+, μ^+, e^+ tracking, particle identification
  - Compact, close to the LXe detector

Mott monochromatic energy spectrum



E_{e+} = 51.8 MeV
σ_E = 412 keV
Momentum center can be tuned

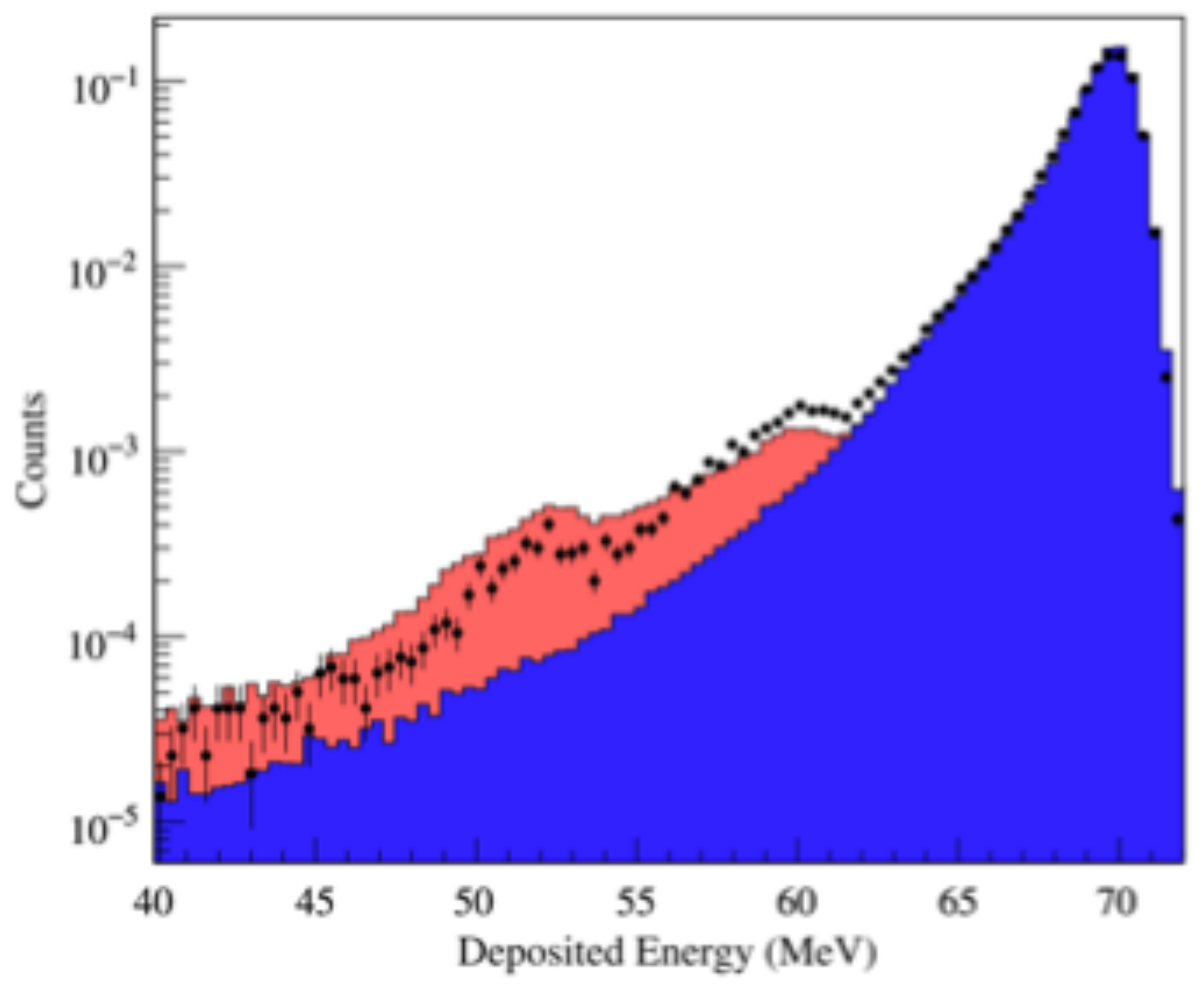


Input E_{e+} = 69.3 MeV
deposit = 55 MeV
σ_E = 1.25MeV(2%)

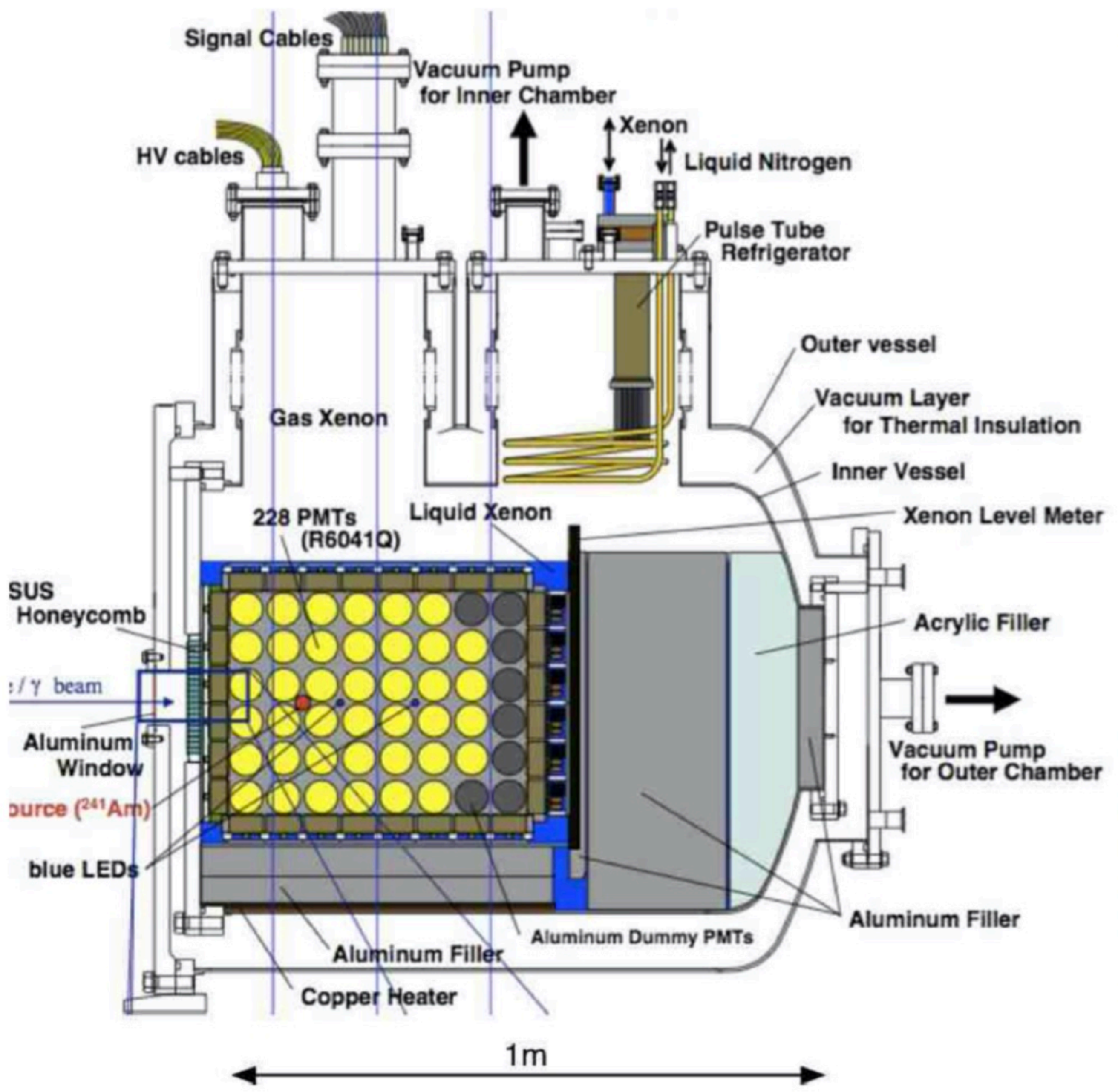
Energy loss at Magnets, we can tune the positron momentum to 83MeV. Still feasible for the detector understanding

Photo-nuclear reaction

- Photonuclear reactions
  - ^{127}I captures γ(electromagnetic shower) → n(94%), p(4%), α(2%) emission → 1n, or 2n escape from NaI → peaks in low energy region
  - This energy region is buried in a large amount of π→μ→e decays, and the detailed spectrum is necessary in advance
- Beam test was performed with positron beam into NaI
- Geant4 simulation should be tuned to reproduce the data.
- We want to test it with LXe, too with the LXe detector or large prototype (~100l LXe)



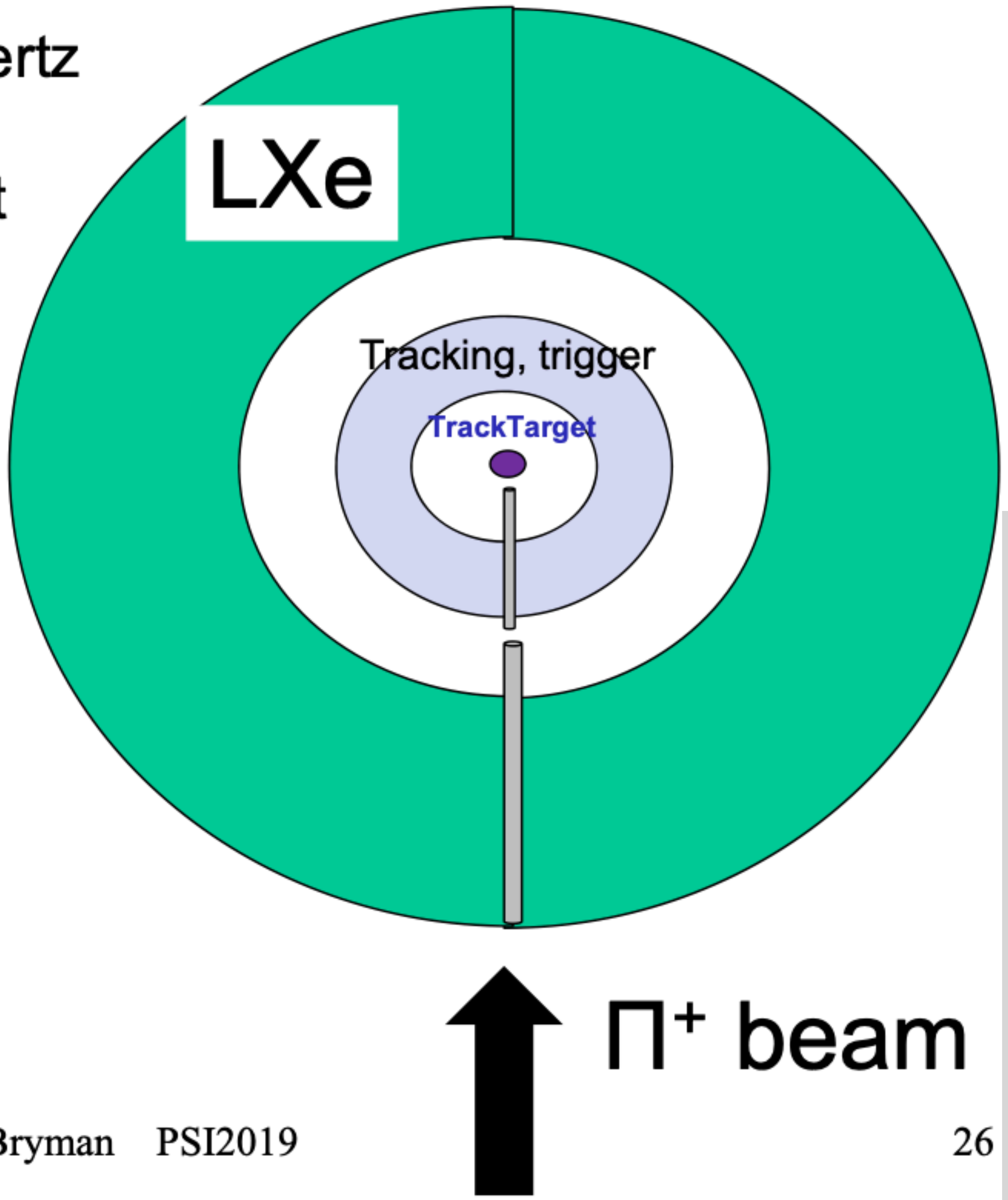
Nucl. Instrum.Meth.A621(2010)188-191



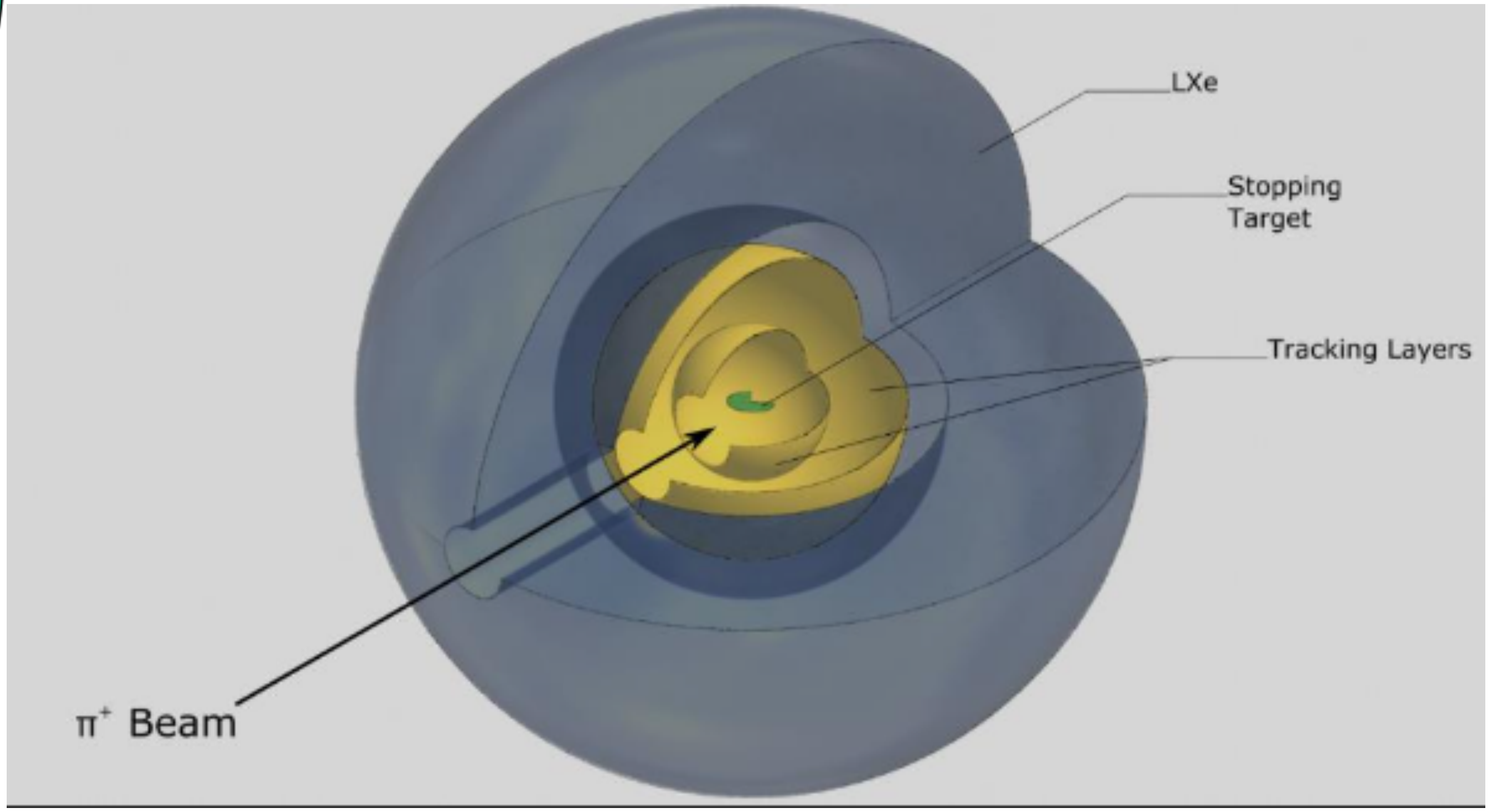
New $\pi^+ \to e^+\nu$ Experiment with LXe?

Douglas BRYMAN

- Π^+ Beam: 75±0.3 MeV/c 10^5 Hertz
- Tracking target – SciFi, SiPMs
- LXe calorimeter – SiPM readout
  - 40 X_0
  - Δt~50 ps, ΔE~1%
- Sensitivity, Precision:
  - 10^8 events
  - ±0.015% in 1 Yr.



10/22/2019   D. Bryman   PSI2019   26



SNOWMASS21-RF2_RF3-048

This is the ideal case,
but we can start many studies with the MEG II LXe detector

Summary

- The MEG II experiment will look for new physics beyond the standard model by studying the $\mu^+ \rightarrow e^+ \gamma$ decay in about three years from 2021.
- The 900 l liquid xenon detector is used for the γ detection.

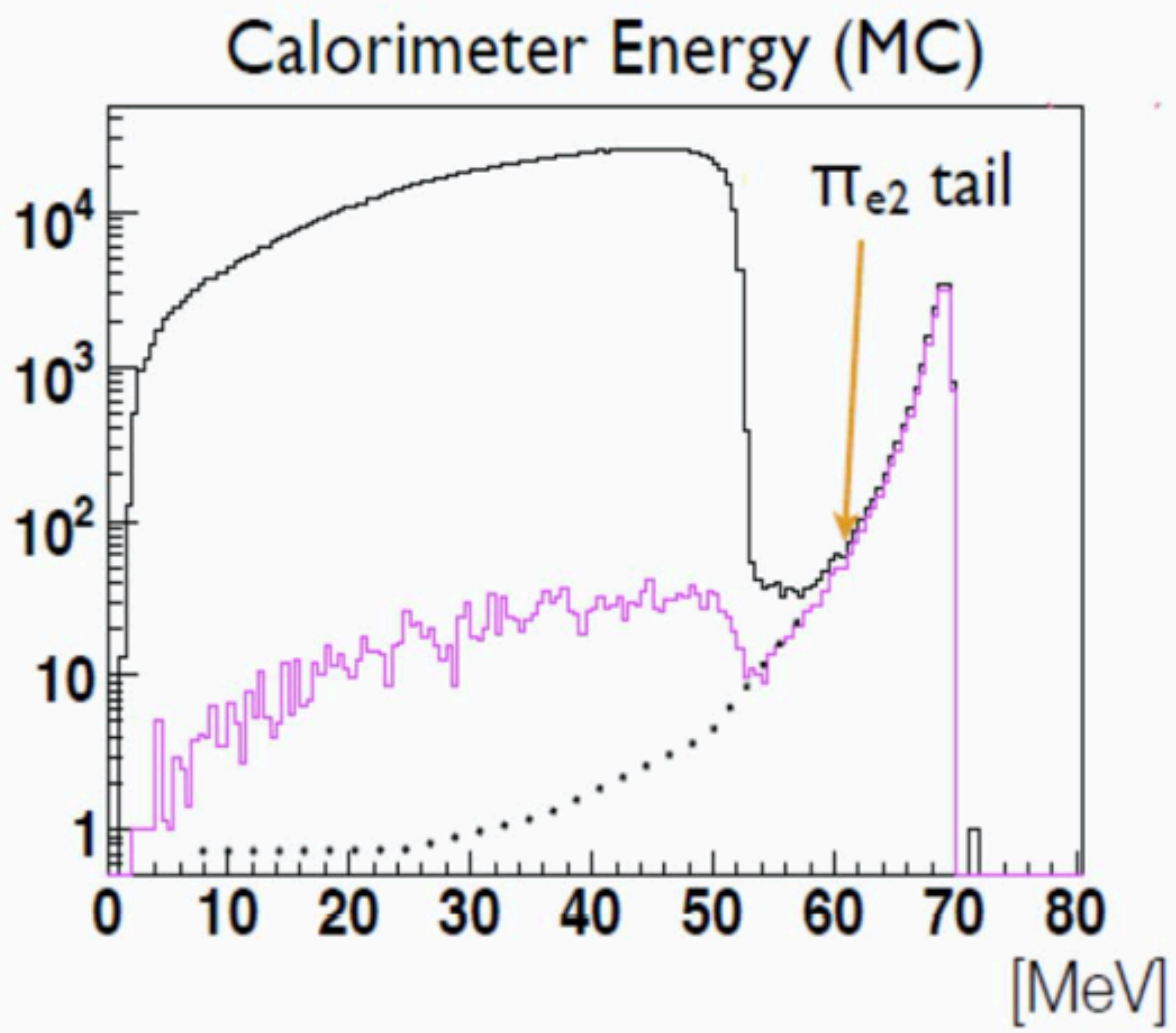
- We started investigating if the MEG II liquid xenon detector can be utilized for lepton flavor universality violation search to precisely measure the ratio of $R = (\pi^+ \rightarrow e^+ \nu) / (\pi^+ \rightarrow \mu^+ \nu)$
- We will estimate which sensitivity can be reached by the existing the MEG II liquid xenon detector by using the simulation and the real data.

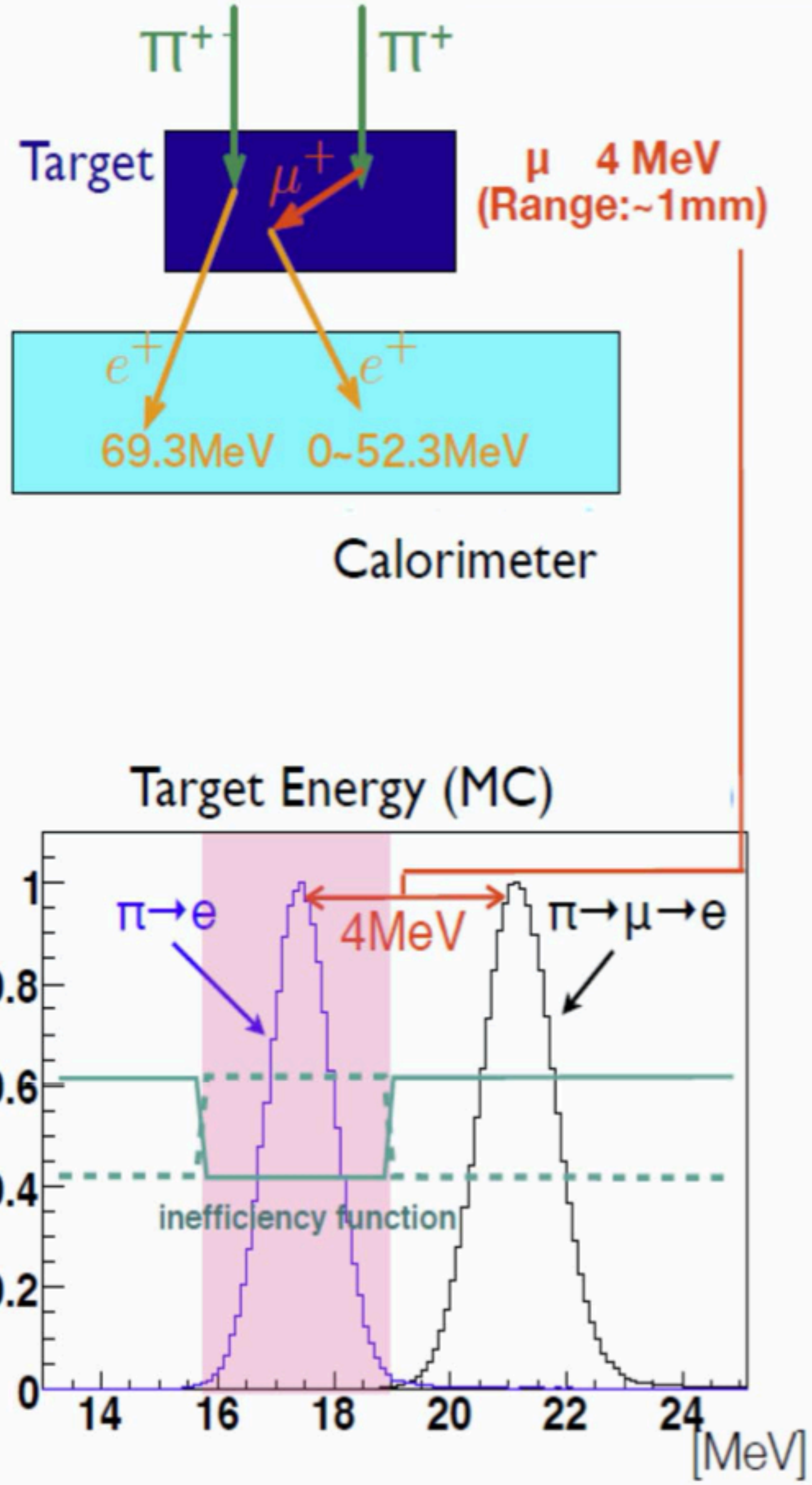
- If you have any good idea to be tested even in this MEG II configuration, please let me know.

backup

Exp. Method

•Pions stop in an active target.
•Out-going positrons are detected by a calorimeter.
•Tag decay modes by calorimeter energy.





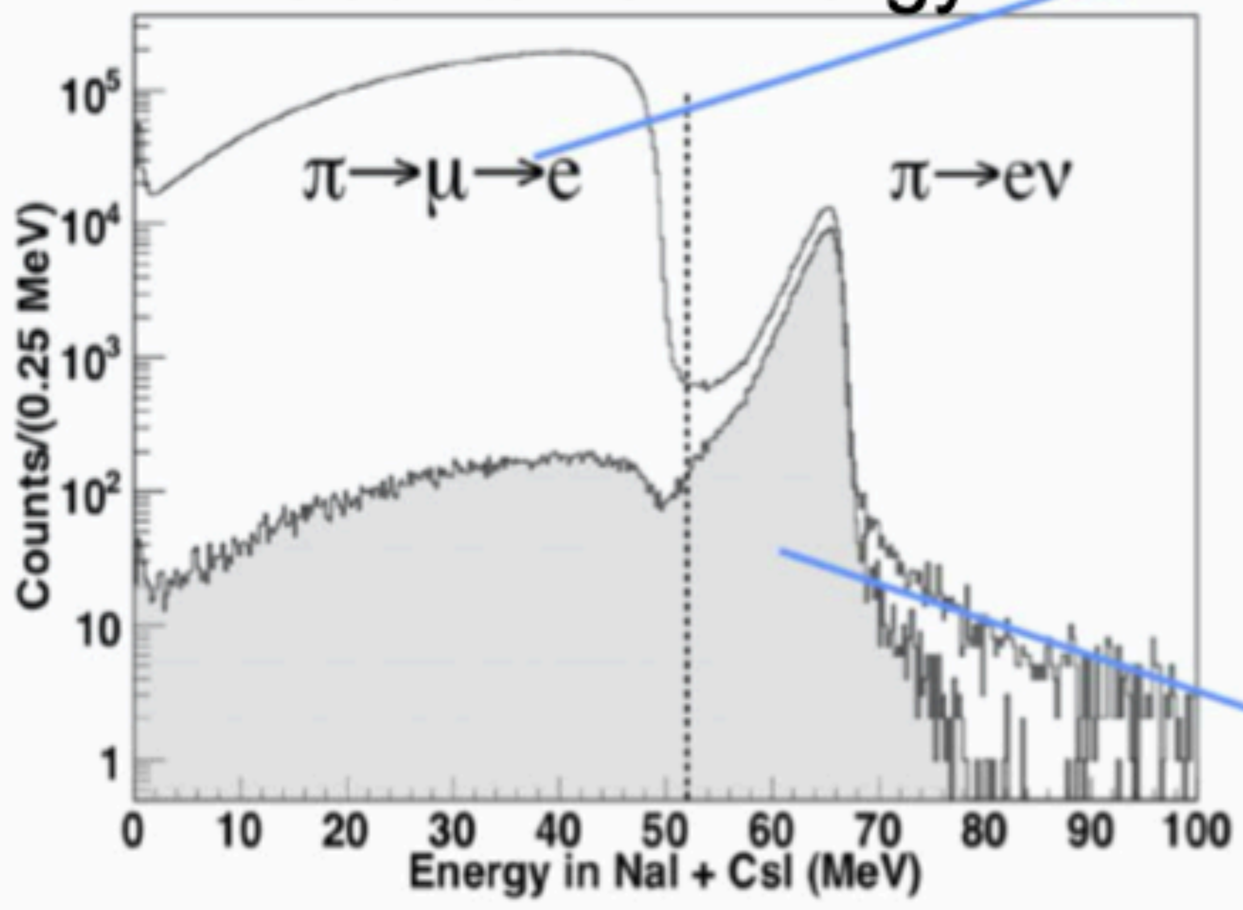
•Low-energy tail of π_{e2}: should be corrected.
•Use target energy to **"blind" the result:** hidden random target-energy-dependent inefficiency.

PI E NU

2015 publication

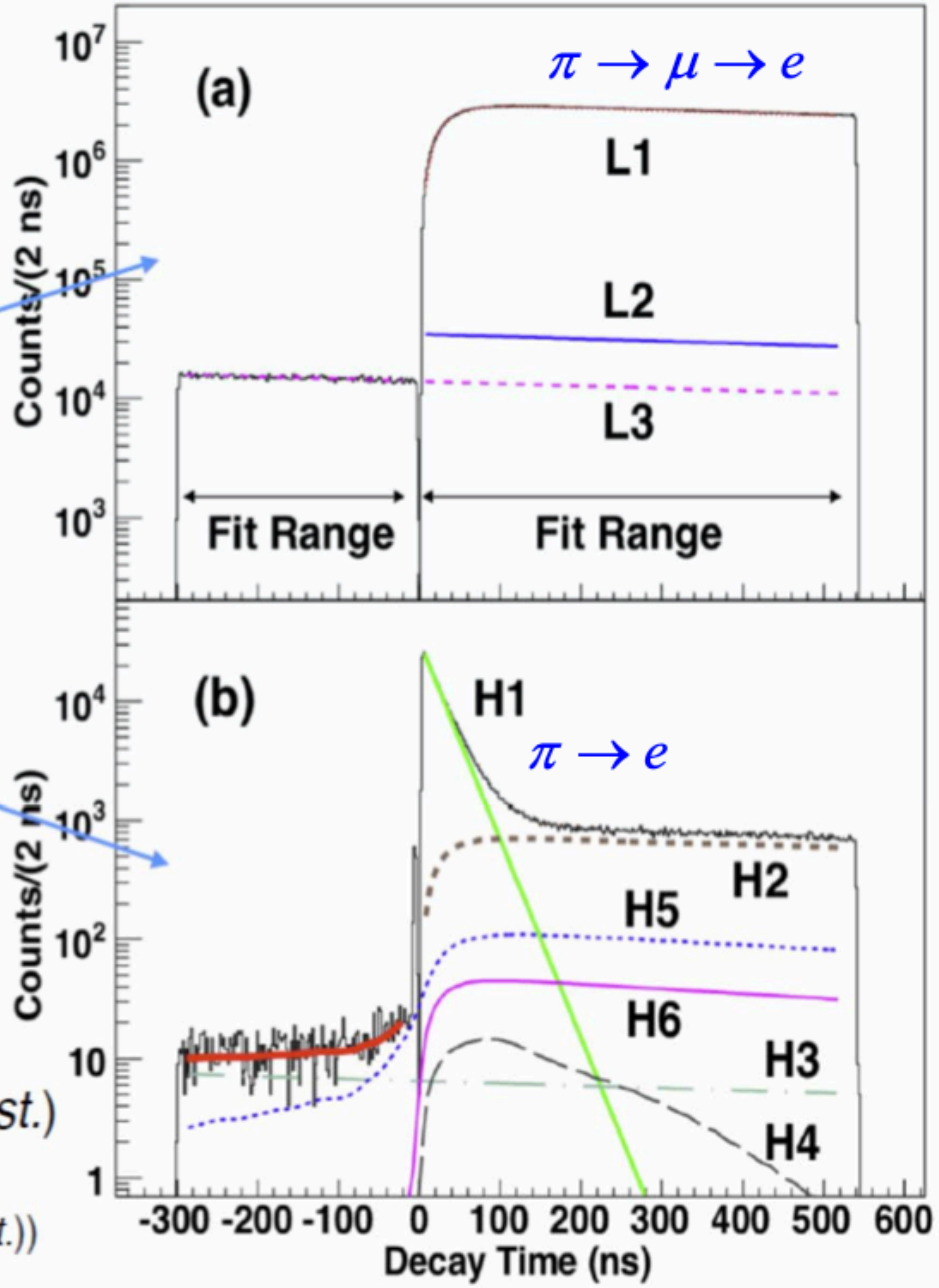
2010-data: 0.4 M $\pi^+ \to e^+ \nu$

Counts vs. Energy



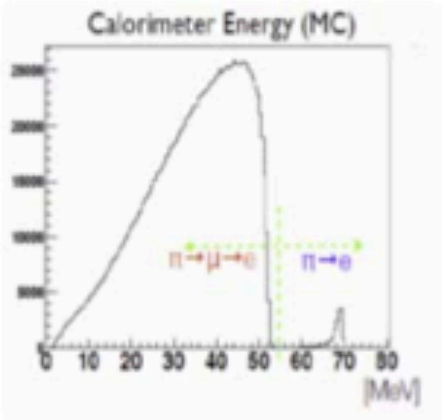
Every spectra of positrons in the time region 5—35 ns.

Counts vs. Time



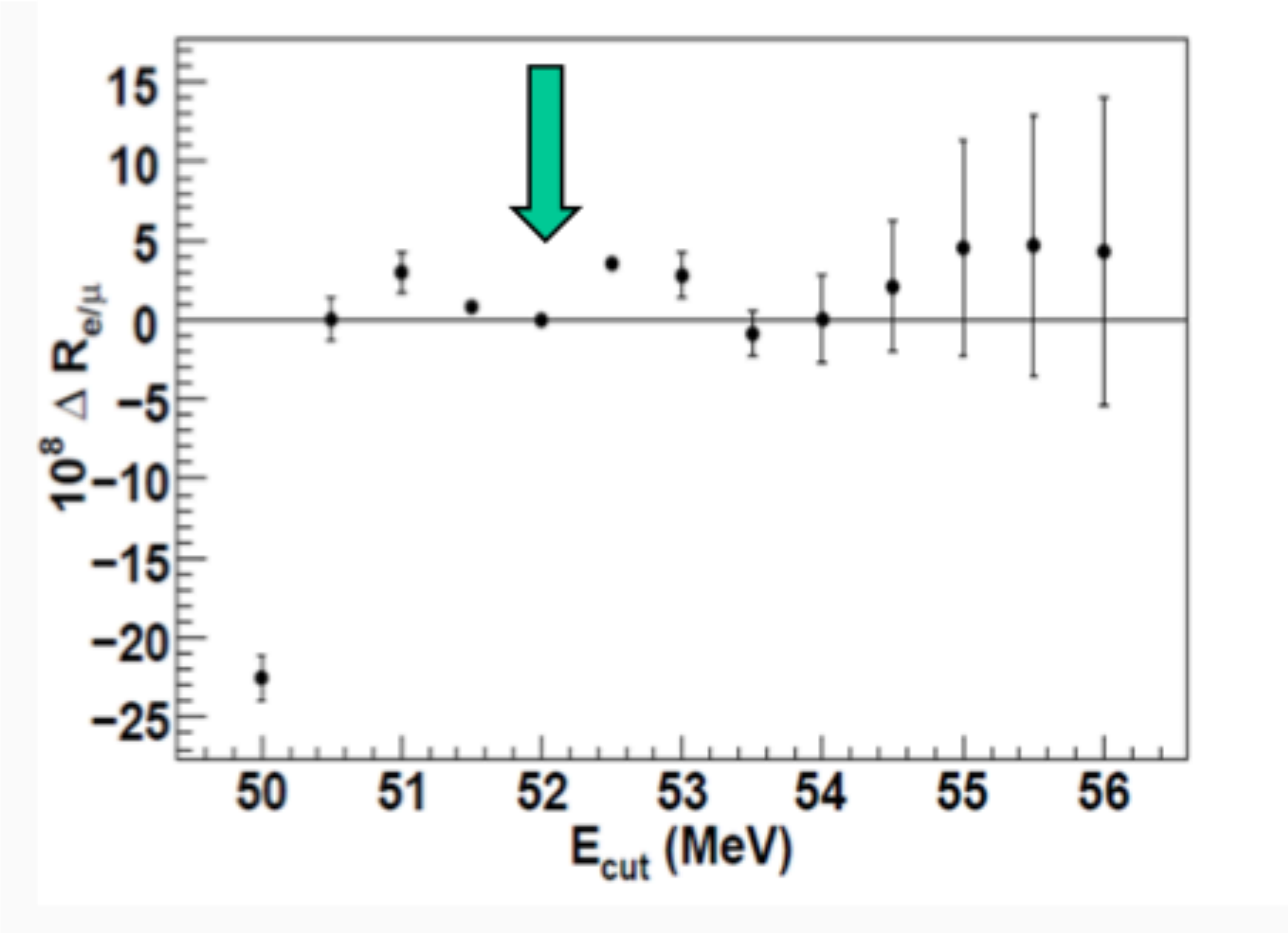
$R = 1.2344 \pm 0.0023(\textit{stat.}) \pm 0.0019(\textit{syst.})$

$(R_{@1992} = 1.2265 \pm 0.0034(\textit{stat.}) \pm 0.0045(\textit{syst.}))$



PI E NU

$R^{\exp\pi}_{e/\mu}$ dependance on E_{cut}



PIENU Uncertainties

Error	PIENU 2010	PIENU goal
Statistical	0.19%	0.07%
Time Spectrum	0.04%	0.04%
Tail Correction	0.12%	0.06%
Others	0.07%	0.04%
Total	0.24%	< 0.1%

Current Result PIENU: $R^{\exp\pi}_{e/\mu} = 1.2344 \pm 0.0030x10^{-4}$: $\frac{g_e}{g_\mu} = 0.9996 \pm 0.0012$

Full Data Sample: 10^7 $\pi^+ \to e^+\nu$ Events

Precision Goal: $\pm 0.1\%$ (Coming Soon!)

https://s3.cern.ch/inspire-prod-files-e/ee196c6df1926b10719b9267edf15604

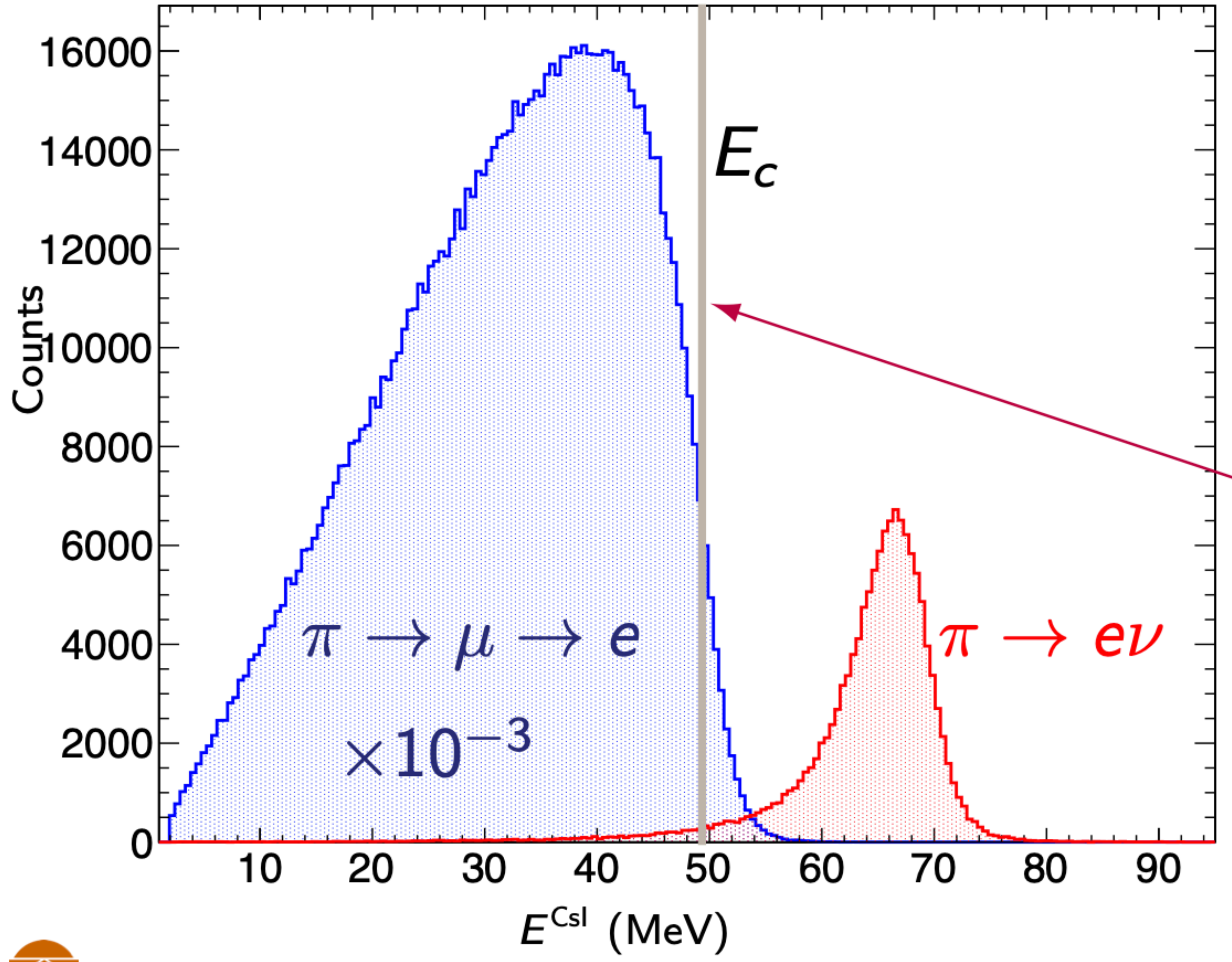
Experimental branching ratio ($R^{\pi\text{-exp}}_{e/\mu}$)

Knowing that:

- timing gates affect the analyzed number of π_{e2} and $\pi \to \mu \to e$ events;
- MWPC efficiency depends on energy,

we have:

$$R^{\pi\text{-exp}}_{e/\mu} = \frac{N^{\text{peak}}_{\pi\to e\nu}(1+\epsilon_{\text{tail}})}{N_{\pi\to\mu\nu}} \underbrace{\frac{f_{\pi\to\mu\to e}(T_e)}{f_{\pi\to e\nu}(T_e)}}_{r_f} \underbrace{\frac{\epsilon(E_{\mu\to e\nu\bar{\nu}})_{\text{MWPC}}}{\epsilon(E_{\pi\to e\nu})_{\text{MWPC}}}}_{r_\epsilon} \underbrace{\frac{A_{\pi\to\mu\to e}}{A_{\pi\to e\nu}}}_{r_A}$$



E_c = cutoff energy

N = number of events

A = acceptance

$\epsilon_{\text{tail}}(E_c)$ = tail to peak ratio

$\epsilon(E)_{\text{MWPC}}$ = efficiency of MWPC

$f(T_e)$ = decay probability during observation time window

This study

- Limitation of the previous experiments
  - Statistic uncertainty
  - Systematic uncertainty
    - Spectrum shape at low energy region due to shower leakage of NaI/CsI
- replace NaI/CsI with LXe for positron detection
  - Possible to reduce shower leakage?
  - Comparable energy resolution
  - Large & uniform positron detector (66 cm × 140 cm × 38.5 cm)
    - 48 cm diameter × 48 cm depth NaI (PIENU)
- Goal
  - Data statistics 10^7 ($\pi^+ \to e^+\nu$) events → 10^9 events
    - Acceptance 20%→50%
    - Data taking 100 days → 365 days
    - Beam rate 7×10^4/s → 3×10^5/s
  - The well understood detector already exists, and quick start is possible
    - Large volume with uniformity, less systematics
  - Smaller systematic uncertainty with beam test for photonuclear effects (with large statistics)
  - In total, we will aim at 0.01% uncertainty comparable to the theory uncertainty
  - A full experimental design in four years